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INVESTIGATION TO DETERMINE THE EFFECT OF PHASING ON THE NOISE GENERATED BY SPUR GEARS

Task 9R38-01-017-54

Contract DA 44-177-TC-777

April 1962

prepared by:

VERTOL DIVISION
THE BOEING COMPANY
Morton, Pennsylvania

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U. S. ARMY TRANSPORTATION RESEARCH COMMAND
Fort Eustis, Virginia

The noise measurements and analysis conducted in preparation of TREC Technical Report 61-72, "Study to Establish Realistic Acoustic Design Criteria for Future Army Aircraft", indicated that noise levels of all Army helicopters exceeded acceptable limits. Narrow-ban analysis of measured noise levels revealed that the main transmissions were, in most cases, the main source of internal helicopter noise. Efforts by other investigators to reduce gear-generated noise have been directed primarily toward tolerances, surface finish, and gear-tooth form. Although these parameters have been shown to affect gear noise, there are obvious limits to the manufacturing tolerances that are realistic for production gearing.

The purpose of this investigation was to determine whether other design parameters have an effect on gear-generated noise and whether these parameters are sufficiently significant to warrant further investigation.

The tests conducted indicated that tooth phasing, the torsional elastic properties of the system, and the gear-case stiffness distribution may all have significant effects on gear-generated noise.

This Command concurs in the conclusions and recommendations expressed in the report, and continuation of this investigation will be recommended for inclusion in future research programs.

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FOR

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FORT EUSTIS, VIRGINIA

PREFACE

This report was prepared by C. L. Muehl and H. Sternfeld, Jr., of the Vertol Division of The Boeing Company under Contract DA44-177-TC-777, Task 9R38-01-017-54. It was funded by the U. S. Army Transportation Research Command, and was conducted under the technical cognizance of Mr. J. Everette Forehand, U. S. Army, TRECOM, Fort Eustis, Virginia.

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LIST OF SYMBOLS

A_H	surface area of hemisphere, ft^2
db	decibels
DI	directivity index
IL	intensity level, db re 10^{-16} watts/cm^2
$\overline{IL_H}$	average intensity level over hemisphere, db re 10^{-16} watts/cm^2
$\overline{IL_s}$	average intensity level over sphere, db re 10^{-16} watts/cm^2
n	test point
PWL	power level, db re 10^{-13} watts
SPL	sound pressure level db re .0002 dynes/cm^2
SPL_s	total sound pressure level over sphere, db re .0002 dynes/cm^2

SUMMARY AND CONCLUSIONS

A test program was performed to evaluate the effect of relative gear tooth contact phasing on the acoustical characteristics of a model transmission.

It was concluded that within the limitations of the test configuration, the radiated noise frequency characteristics for a constant tooth contact frequency are a function of the number of gear sets, while the amplitude and directional characteristics are a function of their relative phasing.

It was also noted that changes in the torsional elastic properties of the system produced significant changes in radiated noise.

RECOMMENDATIONS FOR FUTURE STUDY

The subject study may be regarded as a pilot project to determine whether costly full scale testing of helicopter transmissions for effect of gear phasing on generated noise is warranted.

Although the results of this program appear to justify such a full scale program, it is recommended that additional model tests be performed to first evaluate:

a. The effects of gear quality on sound power

b. The effect of system torsional stiffness on frequency

Another group of studies, which the current program has revealed as worthy of further investigation which could also be carried out utilizing the test facility designed and built under the subject contract, would include:

a. More detailed theoretical and experimental studies to correlate case motion and radiated noise

b. Control of generated noise by case volume

c. Control of radiated noise by case stiffness distribution

d. Effect of gear noise on typical fuselage structures and the relative effectiveness of various fuselage structural damping methods

I. INTRODUCTION

Rotor-craft designers, in the past, have been confronted with several major problems whose solutions were required before general acceptance of the helicopter was possible. One of these has been relatively high internal noise levels. A recent study (Reference 1) has shown that the predominent internal noise has long been associated with the transmission gearing and helicopter crews have frequently reported "ringing ears" due to rotor transmission frequency noise. Such high noise levels contribute to crew fatigue, interfere with radio communication and generally reduce flight-crew response and morale. Cases of actual hearing damage at the frequency generated by the transmissions have been known to result in grounding of experienced pilots and flight personnel.

Currently, treatment of gear noise is handled in a manner similar to other aircraft noise in that acoustical blankets are employed to achieve transmission loss and absorption within the aircraft cabin. The use of damping tape on the fuselage has improved noise levels in certain applications and, where necessary, transmission enclosures have been built to further contain the noise. The weight associated with such treatments has steadily increased as aircraft gross weights have increased, and only by attacking the problem at its source, i.e., by reducing the noise generated by the gears themselves, as well as that amplified by the gear case, is it likely that soundproofing weights will be appreciably reduced.

This program is primarily an investigation of the effect of phasing on the noise emanating from a gear box. Sound transmission in air is accomplished through propagation of waves, which, for most purposes of practical application, are sinusoidal in nature. In theory, addition of two sine waves, identical in frequency, which are separated in phase would produce a third wave of the same frequency but of yet a third amplitude. While gear noise may not be sinusoidal, it can be phased, and the subject study investigates the effects created by phasing.

Sound power levels radiated from the gear box, along with directivity indexes are used as the primary measures of the aforementioned acoustical effects.

II. DESCRIPTION OF TEST EQUIPMENT

TEST STAND

The ideal test stand for a study of gear noise as a function of the phase of tooth contact frequencies should (1) contain two gear noise sources whose only variable is phase and (2) should have silent auxiliary equipment. The following is a description of the actual test stand which, within practical limits, was designed to meet the above specifications.

In general, the test stand consisted of two identical sets of spur gears driven by a common shaft (Figure 1). Phasing was provided by an indexed coupling between the two driving gears. Loading was accomplished by driving two 12 kw d-c generators which, in turn, dissipated the load through calibrated resistive load banks (Figure 2). Sound pressure level measurements were made with the aid of a semicircular microphone location hoop (Figure 2).

Spur gears were chosen rather than helical because the planetary gears in helicopter transmissions are usually spur gears and because the generated noise level of spur gears is higher and thereby simplifies the problem of isolating the noise sources from the auxiliary equipment. A low contact ratio (1.52) was chosen to maximize the noise level source.

To obtain a tooth contact frequency which is representative of normal helicopter transmission frequencies (400 cps - 800 cps), the 18 tooth gears were driven at 1750 rpm, resulting in a tooth contact frequency of 525 cps. Isolation of vibratory loads from the driving motor and gear loading devices was accomplished by the use of belt drives.

Phasing of the gears was accomplished by means of an indexed flange coupling (Figure 1). Rotating one side of the flange one position relative to the other advances the driving gear of one set seven-sixths of a tooth space or $23^{o}20'$ relative to the driving gear of the other set. Since the pitch angle is 20^{o} for 18 tooth gears, the resultant tooth mesh phase difference is $3^{o}20'$.

The fact that gear noise, before it is airborne, must first be absorbed and reradiated by the gear case necessitates measuring the gear case response as a function of phasing. The gear case (Figure 1) was a simple rectangular box, the large, flat, unobstructed areas of which provide ideal surfaces for response measurements. Isomode pads provided isolation of the gear case from the table.

As stated earlier, an ideal test stand would have the noise sources easily separable from the noise of the auxiliary equipment. This requirement could be met in part by creating a noise source level that would be large with respect to ambient noise. With this point in mind, the gears were operated at the optimum load of 212 amps as shown in Figure 3; that is, the load at which the gear noise is a maximum relative to other noise sources without causing undue wear of the mating gear teeth. (See Appendix I)

The loading devices were d-c generators coupled to resistive loads. The conversion of mechanical energy to heat through the use of the d-c generator and load combination offered at least three advantages: (1) quietness of operation in power dissipation, (2) variable gear loading obtainable by varying load resistance, (3) ease of power measurement by instrumentation of the load bank for output voltage and current drain. Shaft speed was determined by a hand held tachometer. The above instrumentation was used to measure the magnitude of the gear loads, to assure that both sets of gears were loaded equally, and to assure that all sound pressure level data were recorded under similar conditions.

All measurements and calibrations were made in accordance with the method described in Reference 2. To provide a proper environment for measurements, the noise source must be above a hard, smooth reflecting surface which is free from obstacles. The steel table top (Figure 2) satisfies this requirement and also serves as a barrier to airborne motor and generator noise.

To determine power levels and directivity from sound pressure levels, the points of measurement (1) must be the same distance from the noise source center, (2) must be in the free field and (3) must be in the centers of equal areas on a hemispherical surface. Requirements 1 and 3 were satisfied by the use of a semicircular guide (Figure 2). Microphone positions (Figure 4) were secured in azimuth by rotating the guide to indexed positions and bolting to the table top. The microphone was located in elevation by means of quick release clamps attached to hoop. Initially, the microphone was to be isolated from the measurement hoop by providing a flexible foam between the microphone and the closed clamp. Preliminary measurements, however, proved the above isolation inadequate (Figure 5); therefore, it was necessary to physically separate the microphone from the hoop. Figure 2 illustrates the measurement method necessary to provide adequate isolation. Reflection from the operator's body was avoided by attaching the microphone to a long pole. Reference 2 also requires that the hoop radius be greater than the wave length of the lowest frequency of interest. For practical reasons the hoop radius was limited to three feet, resulting in a low frequency limit of 366 cycles per second. However, the test stand was designed to have a tooth contact the frequency of approximately 520 cps; therefore, a hoop of the size employed is completely satisfactory for this study. As previously mentioned, all sound pressure level measurements must be made in the free field. The test site (Figure 6) was chosen such that this requirement was met. Specifically all significant reflecting surfaces or noise sources are at least 75 feet from the test stand. The load was purposely located adjacent to the test stand so as to be in the acoustical shadow of the table top.

INSTRUMENTATION

Generally, the instrumentation used can be classified according to its function: measurement instrumentation and analysis instrumentation. The measurement instrumentation classification includes airborne noise measurement equipment, structure-borne vibration measurement equipment, and load power measurement equipment. The analysis grouping includes instrumentation necessary to provide sound pressure level and vibratory displacement amplitudes as functions of frequency. A detailed list of all instruments can be found in Appendix II.

Calibration procedures are described in detail in the systems calibration section of this report. The objectives of all calibrations were to assure a flat frequency response and to maintain a uniform system sensitivity.

Calibration of Airborne Noise System

In order to assure good frequency response of the Ampex 601 tape recorder, complete alignment procedures for equalization, hum, bias, and head adjustments as outlined in Reference 3, the "Operation Maintenance Manual" for an Ampex 601 tape recorder were followed. The frequency response plot (Figure 7) indicates that the recorder was within the manufacturer's specifications: ± 2 db from 50 to 10,000 cps.

Manufacturer's data was used as basic calibration information for the microphone itself. To allow for small changes in electrical characteristics, a sensitivity check was made of the entire recording system at appropriate intervals throughout the test. The standard for this check was a 400 cps signal produced by a transistor oscillator. The oscillator signal provides the power to drive a small loudspeaker contained within a sound level calibrator. The loudspeaker is placed directly over the system's microphone, the oscillator signal is adjusted to two volts, and 121 db calibration signal is then recorded on the system's magnetic tape recorder. This calibration signal when played back through the analysis equipment is then used as a reference level.

Calibration of Structure-Borne Vibration System

Appendix II lists and identifies the vibration measurement instrumentation. Figure 8 illustrates the physical arrangement of the test equipment necessary to perform the calibration and also indicates the system's response characteristics.

System sensitivity checks were made in a manner similar to the sensitivity check of the airborne noise measurement equipment. The standard in this case was a 0.5 volt, 400 cps signal from the transistor oscillator and was used to determine the electrical sensitivity of the system, excluding the accelerometer. The manufacturer's calibration of the accelerometer was accepted as valid, because only relative displacements were desired.

Calibration of Power Measurement System

As explained previously, the loading system for the gear box consisted of direct current generators and resistive load banks. Power could be determined, therefore, simply by reading the voltage across any load bank and the current drain. To correct for instrument error, both load banks were connected in series with one generator, and ammeter indications were noted for various load conditions. Using this data and plotting one set of ammeter readings against the other (Figure 9), relative ammeter instrument errors were determined. By the use of a switching arrangement, only one voltmeter was used to measure voltage across either load bank. Therefore, no correction for voltmeter instrument error was required.

Calibration of Analysis Systems

The purpose of the analysis instrumentation was to provide data by which SPL and amplitude displacement due to vibrations could be plotted as a function of frequency. Provisions were made to plot SPL as a function of frequency in octave bands and as a line spectrum.

Frequency response of the octave band analyzer was checked by providing a signal of constant level but varying frequency at the input of a selected octave band filter and noting the output level. The results of this calibration along with a sketch of the instrumentation used are illustrated in Figure 10. As explained previously, calibration signals were recorded at intervals throughout the test to correct for changes in system sensitivity. The octave band analyzer has a movable reference dial whereby the indicating meter can be made to read 121 db corresponding to the 121 db calibration signal. The output of the narrow band analyzer was displayed on a graphic recorder. The same calibration signal, when played back through the narrow band analyzer and recorded by the pen on the graphic recorder, provides the data point by which the ordinate of the strip chart can be calibrated.

III. DESCRIPTION OF TEST PROCEDURE

The general procedure used throughout the test was designed to obtain maximum accuracy with a minimum of running time on the gears. Thus, the procedure followed a pattern which minimized movement of the operator, by an ordered survey of test points and orderly arrangement of equipment, while still maintaining a check on the variables which might affect the results. The precautions which were taken to ensure accurate test data are outlined below.

Before the start of each run, weather conditions were noted. In particular, a check was made of the effect of wind noise as monitored on the tape recorder's volume units meter. Although an octave band analysis of wind noise indicated it affected only the first three octave bands (20-75 cps, 75-150 cps and 150-300 cps), data was recorded only if the wind noise was at lease 20 db below the overall sound pressure level generated by the gear box, approximately 15 mph. A wind screen was placed over the microphone to minimize the effect of wind noise further.

Sensitivity calibration records of the entire recording system were taken at the beginning of each run and at appropriate intervals throughout the test. The serial numbers of every component of the instrumentation system were listed on each data sheet. To avoid a possible error due to equipment substitution, all component serial numbers were checked against the list on the data sheets.

Microphone data at the locations shown in Figure 4 and accelerometer data at 12 points uniformly distributed over the box cover (Figure 1) were not taken simultaneously but within as short a time interval as possible to ensure consistency.

Several times during each run the gear-shaft speed was monitored with a hand-held tachometer, and load bank data, volts and amperes, were recorded. More frequent readings were not warranted because of the unappreciable change of loading during a run.

As discussed in Section II, the microphone was secured to the end of a long hand-held rod, and was located by means of the measurement hoop. Caution was exercised to avoid contact with the hoop, therefore eliminating the possibility of recording structure-borne noise.

The accelerometer was attached to the top of the gear box by means of "double-backed" tape, which proved satisfactory for this purpose and provided the fastest and most efficient means of changing accelerometer positions.

All data was recorded on an Ampex 601 tape recorder at a tape speed of 7-1/2 inches per second.

IV. DESCRIPTION OF ANALYSIS PROCEDURES

As stated in Section II-2, all the data obtained was analyzed using full octave bandwidth filters, while selected data of special significance was subjected to continuous wave analysis.

The first step in converting original magnetic tape data to sound power levels, directivity indexes, and double amplitude displacements was to reduce the airborne noise data to sound pressure levels in octave bands and the structure-borne vibrations to an accelerometer output voltage.

The octave band analyzer, General Radio Type 1550-A, contains eight band pass filters, any one of which can be selected by a switch. During the data acquisition, a sensitivity calibration (400 cps) signal was recorded along with the test data, the level of the calibration signal being 121 db. Before the performance of an octave band analysis, this signal was put through the analyzer and the attenuator, and movable reference dials were adjusted so that the indicating meter was calibrated to read 121 db. Following a sensitivity calibration of the analyzer, the data was played back through the octave band filters and the sound pressure levels were read from the indicating meter.

A similar sensitivity calibration of the structure-borne noise analysis system was made before accelerometer output voltages could be determined. A recorded accelerometer calibration signal of 400 cps with a level of 0.5 volts was played back through the selected octave band filters and the level was read out on the voltmeter. All sensitivity calibration levels were referenced to the original calibration signal at phase angle zero, and thus a correction was made for changes in system sensitivity.

The following illustrates the method by which original data in the form of sound pressure levels and accelerometer output voltages were reduced to final data, sound power levels, directivity indexes and double amplitude displacement. Determination of power levels fundamentally was accomplished by determining the intensity of the acoustic power radiated through a known area and multiplying that intensity by the area as described in Reference 2. The first step, therefore, was to convert sound pressure levels to intensity levels. Common practice is to choose a reference intensity (10^{-16} watts/cm^2) and a reference sound pressure (.0002 dynes/cm^2) such that intensity level can be made equal to sound pressure level.

As noted in Section I, the microphone locations are positioned to be in the center of equal areas on the surface of a sphere. Because the hemisphere base equally divides the measurement area associated with the microphone positions near the table top for Positions 3, 4, 11 and 12, the power radiated per unit area is doubled. To correct for this, 3 db was subtracted from the SPL measurements at those points.

The average intensity level over the hemisphere ($\overline{IL_H}$) is then defined as:

(Reference 2)

$$\overline{IL_H} \triangleq \frac{\sum_{1}^{12} IL_n}{10 \log n}$$

IL_n = Intensity level at a given test point

n = Number of test points = 12

The SPL data in the 300-600 band for phase angle zero is repeated here for the purpose of demonstrating the method by which $\sum_{1}^{12} IL_n$ is determined.

Mic. Pos.	1	2	3	4	5	6	7	8	9	10	11	12
SPL_n	102	103	96	105	95	98	90	98	100	100	105	107

Converting to IL_n

Mic. Pos.	1	2	3	4	5	6	7	8	9	10	11	12
IL_n	102	103	93	102	95	98	90	98	100	100	102	104

Summing over all microphone positions gives

$$\sum_{1}^{12} IL_n = 111 \text{ db}$$

A similar calculation to determine the overall $\sum_{1}^{12} IL_n$ (20 cps to 10 kc) yielded a result of 112 db. This concentration of acoustic power in the 300-600 band (which contains the gear mesh frequency) was typical for all phase angles.

As noted in Section II, one approach to realizing an ideal test stand was to design the stand so that the ambient noise of auxiliary equipment was insignificant in relation to gear noise. The above observation proves that the design approach was successful and thereby indicates that an analysis of all octave bands would add nothing to the significance of the results; also, narrow band analysis (Fig. 12) proved that the gear mesh frequency dominated the 300-600 cps band.

Continuing with the data reduction and using Equation I:

$$\overline{IL_h} = \sum_{1}^{12} IL_n - 10.8 = 111 - 10.8 = 100.2 \text{ db} \doteq 100 \text{ db}$$

To convert from $\overline{IL}_H$ to power level (PWL), $\overline{IL}_H$ must be multiplied by the surface area of the hemisphere.

$$PWL = \overline{IL}_H + 10 \log_{10} (A_H) \qquad \text{Where } A_H = \text{area of the hemisphere}$$

$$= \overline{IL}_H + 10 \log_{10} 18 \qquad = 2\pi r^2 = 2\pi(3^2) = 18$$

$$= \overline{IL}_H + 17.5 = 100.2 + 17.5 = 117.7 \doteq 118 \text{ db}$$

IV. The directivity index (DI_n) in a given direction corresponding to a point (n) on the surface of the hemisphere is: (Reference 2).

$$DI_n = IL_n - \overline{IL}_s$$

$$= IL_n - (\overline{IL}_H - 3)$$

$$= IL_n - \overline{IL}_H + 3$$

IL_n = intensity level at specific point (n)

$\overline{IL}_s$ = average intensity level over sphere

$\overline{IL}_H$ = average intensity level over a hemisphere

As an example, the directivity index for microphone position 10 for phase angle zero is:

$$DI_{10} = 100 - 100 + 3 = 3 \text{ db}$$

Plots of directivity indexes can be found in Figures 14 through 20. Subsequent to a determination of power levels and directivity indexes a narrow band analysis of selected data points was made, (Figure 12). Equipment used was a Technical Products TP-627 continuous spectrum analyzer and a General Radio 1521-A graphic level recorder. The strip chart was calibrated by playing a microphone calibration signal of known level through the analyzing system. Subsequent data played through the analyzing system were then compared to the level of the calibration signal.

V. DISCUSSION OF RESULTS

Figure 11 shows the relationship between PWL and relative phasing between the two sets of spur gears.

It is noted that, while there is a strong evidence of PWL dependency on phase, the data recorded at 360° does not repeat that recorded at 0° (Curve 1) as might be expected. Further examination of the data revealed that, if the PWL calculation is limited to those points more directly above the box (i.e. Points 1, 2, and 5-10 of Figure 4), the resulting consistency is greatly improved. Although 0° and 360° data represent identical relative phasings, the actual teeth coming in contact with each other are not the same and, therefore, the remaining discrepancy can probably be attributed to cumulative manufacturing tolerances in the gears and box.

It is recommended that future studies minimize this problem by employing driven and driving gears having unequal numbers of teeth.

Specific test runs were made repeating selected data in order to establish repeatability of operating conditions and data acquisition. It was found that maximum deviations were limited to ± 1 db.

Recognizing all deviations in test method, it is still clearly illustrated that the major change in PWL is associated with changes in gear phase.

Returning to Figure 12, which shows continuous wave spectrum at the 180° (maximum) PWL phases, it can be seen that the tooth mesh fundamental frequency of 525 cps is predominant with 2nd, 4th and 3rd harmonics descending in that order. This frequency relationship was true for all points and indicates that although phasing affects the PWL radiated from the transmission, the frequency spectrum remains unchanged.

Accelerations were measured at twelve points uniformly distributed over the surface of the cover plate. The resulting displacements at gear tooth contact frequency are illustrated in Figure 13. The sound pressure field inside the highly reverberent enclosure is extremely complex and defies prediction. The box itself, however, was designed so that cavity and structural resonances were avoided.

Subsequent bang tests on the cover plate showed a natural frequency of about 295 cps which would not be expected to produce significant amplification of the 525 cps fundamental. It can, therefore, be assumed that the responses shown are essentially forced.

It should be remembered that the gears themselves lie approximately on the lines designated 1-2 and 11-12. Since these zones generally display large displacement, this lends further evidence that the deflections are primarily forced responses. It is obvious, therefore, that changing phase of the forcing functions arising from pressure distributions within the box has resulted in significant changes in forced case motion.

The SPL at each microphone position may be thought of as arising from point sources, distributed over the surface of the case, whose energies are functions of the local case velocities at each point. Since each microphone position comes under the influence of pressure waves spreading from each theoretical point, it can be seen that the actual synthesis of measured SPL from measured case motions could be extremely complex. A possible procedure, however, would consist of simultaneous measurement of (n) motion points on the case and SPLs at (n) microphone locations. Solution of an n^{th} order matrix could then be performed to yield influence coefficients which could be used for predicting PWLs corresponding to given case deflections.

Directivity Index as derived in section IV is a measure of the three dimensional directional characteristics of the noise, as opposed to its total power. Directivity indexes are displayed graphically in Figures 14-20. In general, they indicate that, unlike the PWL (Figure 11) and case deflections (Figure 13), the directional characteristics of the energy distribution is relatively unaffected by the gear phasing and are probably dictated by actual case geometry.

Figure 12b shows the spectrum achieved with one set of gears operating. It is most significant that in this case, the fourth harmonic rather than fundamental is accentuated. Since case structure and volume were generally unchanged, as was the primary gear excitation, it appears that the major change in the system due to the uncoupling of the index flange is one of system torsional natural frequency. This is further borne out by comparison of the harmonic levels shown by comparing Figures 12a and b. If no system change were noted except removal of one-half of the excitation, it would be expected that each SPL would decrease by 3 db. Actually the SPL for the first harmonic decreased 22 db, the second harmonic by 4 db; the third harmonic increased 3 db and the fourth harmonic increased 1 db. This implies that when the system was uncoupled, its natural frequency moved from close to the fundamental to somewhere between the third and fourth harmonics. This indication is of great significance and implies a possible control of transmission noise by stiffness and inertia properties.

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APPENDIX I

Under proper operating conditions, gear wear is assumed to be most pronounced during the first few hours of operation and then decreases to an insignificant degree. After about five hours running time had accumulated, during the preliminary check of instrumentation and test stand operation at a load of 373 amps (13.5 hp) per generator, it was noted that an increase in SPL had occurred, Figure 21. As a result of this increased SPL, the gear case was opened for inspection and it was noted that considerable scuffing of the gear teeth had occurred. Corrective action was taken to eliminate the reason for scuffing, and the gears were rotated about their transverse axis in order to use the unscuffed side of the teeth as the new points of impact.

To ensure that the remainder of the test could be completed without encountering variation in noise level due to tooth wear, additional testing was performed. Based on these tests, which consisted of monitoring sound pressure level with varying load in order to determine safe and consistent operation commensurate with high noise levels, a load of 212 amps (8 hp) per generator was selected.

It is most interesting and significant to note that the initial wear problem was detected solely by acoustical measurement and implies that such instrumentation can be developed into a useful inspection and diagnostic technique.

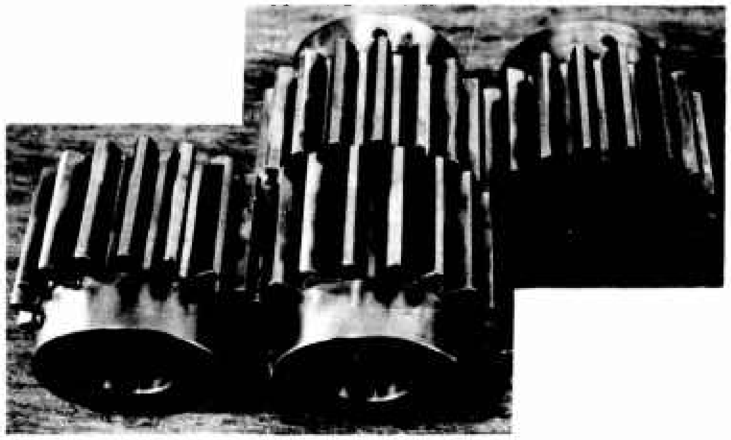
APPENDIX II

LIST OF INSTRUMENTATION

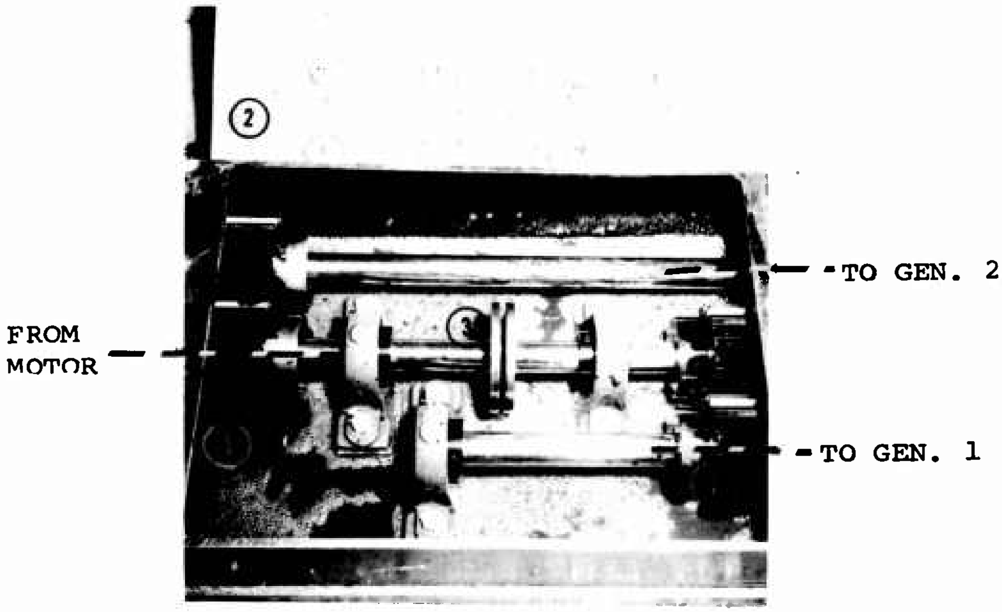
Microphone Base -	General Radio Model 1551-P1-25, S/N 726
Microphone Power Supply -	General Radio Model 1551-P1, S/N 665
Transistorized Oscillator -	General Radio Model 1307-A, S/N 895
Calibrating Speaker -	General Radio Model 1552-B, S/N 1668
Accelerometer -	Endevco Model 2213, S/N R6755
Tape Recorder -	Ampex Model 601, S/N 1234
Octave Band Analyzer -	General Radio Model 1550-A, S/N 703
Standardizer (No. 3) -	Endevco Model 2616, S/N 2742
Standardizer Power Supply -	Endevco Model 2622
Vacuum Tube Voltmeter -	Ballantine Model 300D S/N 1995
Wave Analyzer -	Technical Products Model 625, S/N 187
Graphic Level Recorder -	General Radio Model 1521-A, S/N 157
Tachometer -	Biddle Model 504161, S/N 3355
Ammeter (No. 1) -	Weston Model 271, S/N 103488
Ammeter (No. 2) -	Simpson
Voltmeter (No. 1 and 2) -	Weston Model 271, S/N 103551

APPENDIX III

ILLUSTRATIONS



Angular Relationship of Gear
Teeth at a Phase Angle of 180°



1. Number One Gear Set
2. Gear Box Cover Showing
   Accelerometer Location
3. Phase Coupling (Uncoupled)
4. Number Two Gear Set

Figure 1 - Details of Gear Box

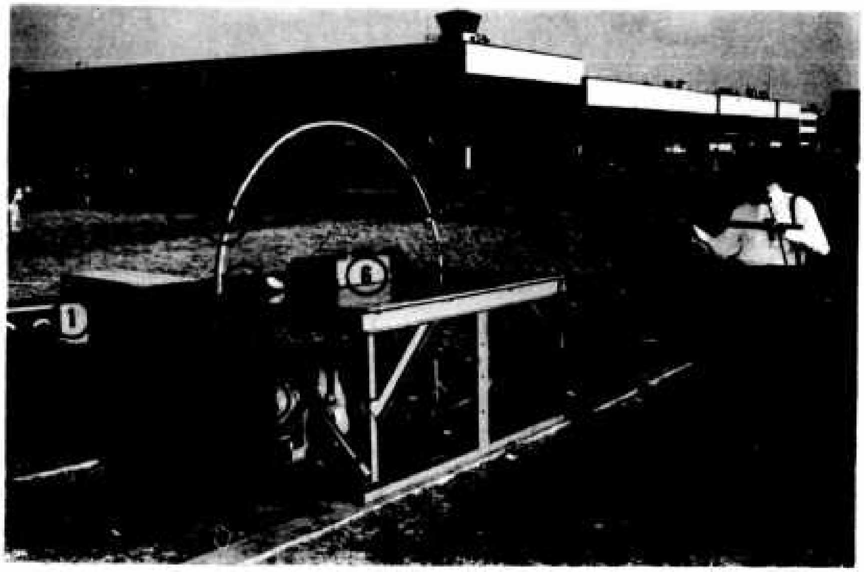


Figure 2. Test Stand with Microphone in Typical Test Position

1. Load Banks
2. Generator Cooling Motor
3. Driving Motor
4. Hand Held Tachometer
5. Microphone Location Hoop
6. Gear Box with Attached Accelerometer
7. Direct Current Generators

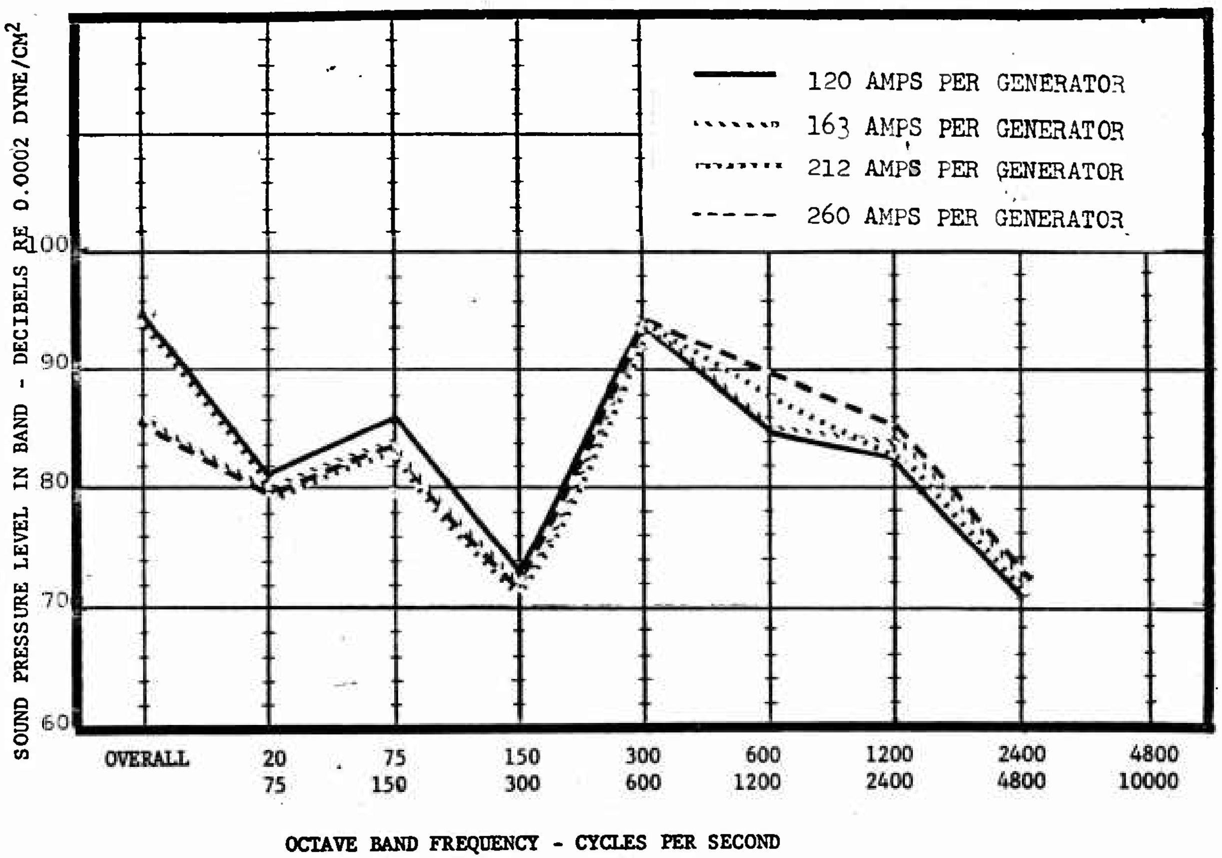


Figure 3. Effect of Load on Sound Pressure Level

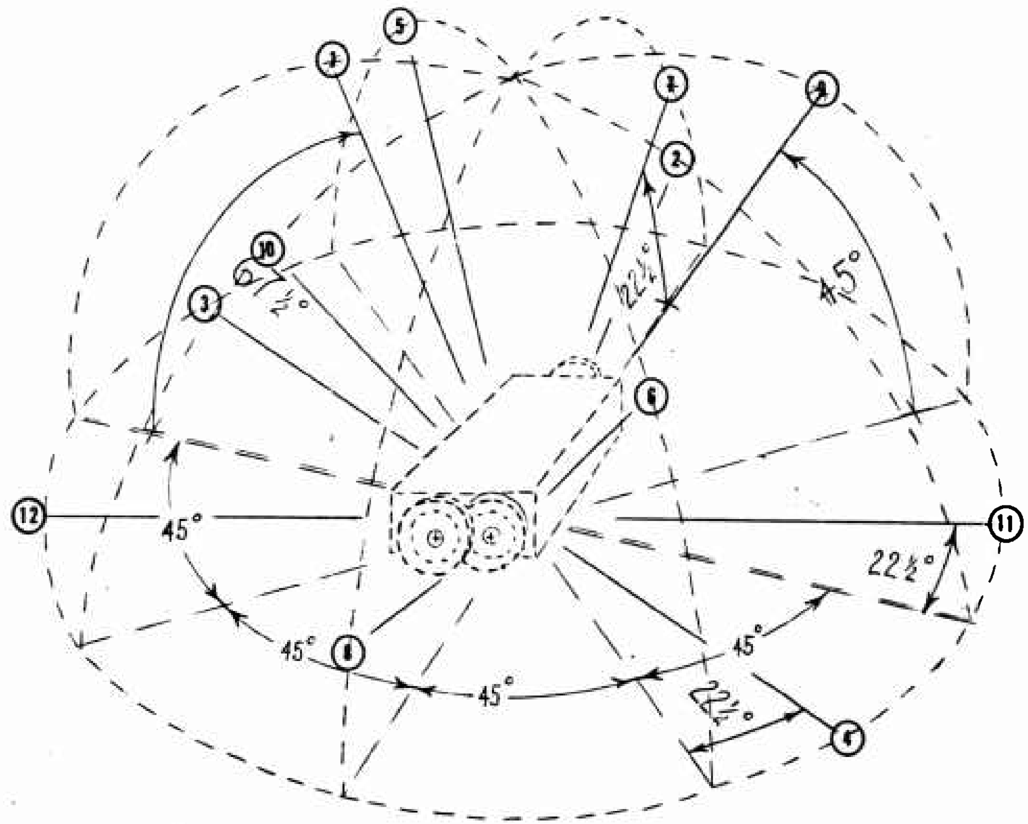


Figure 4. Microphone Locations

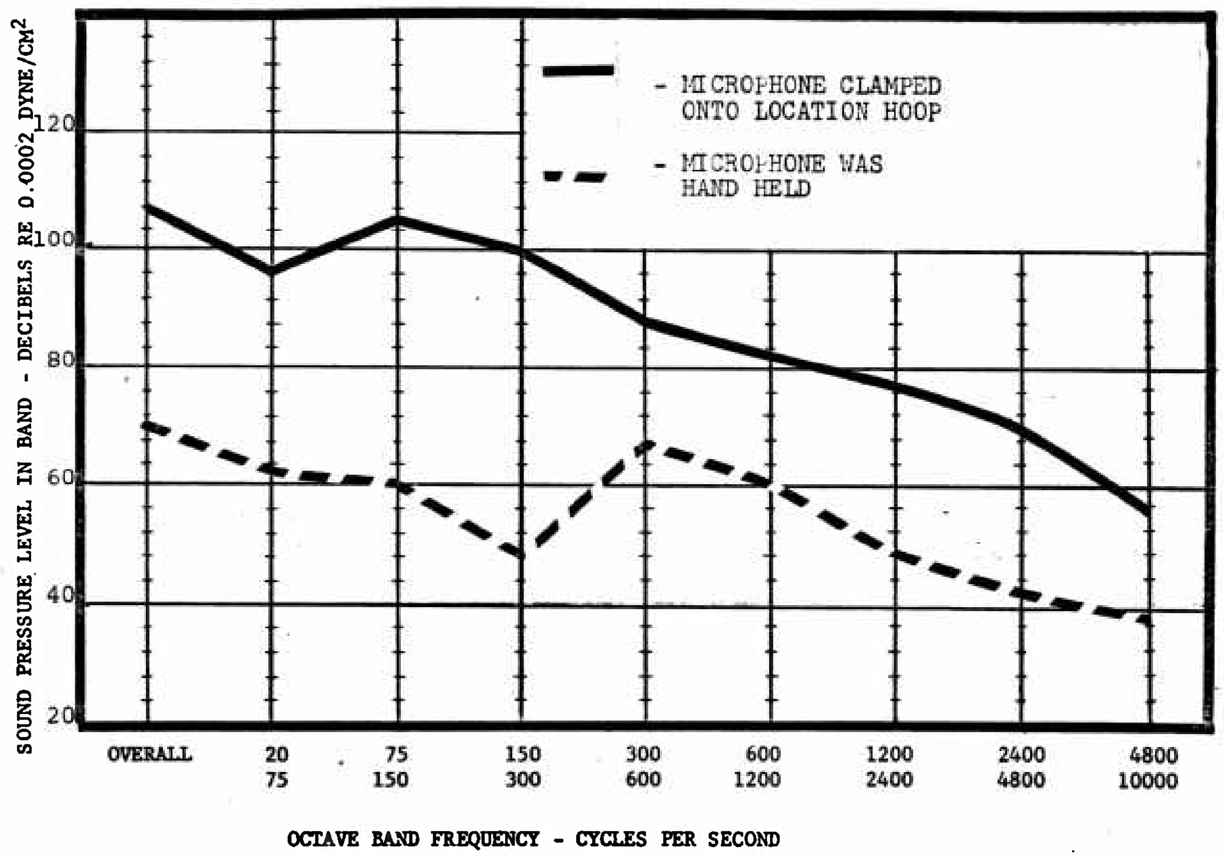


Figure 5. Isolation of the Microphone from Structure-Borne Noise

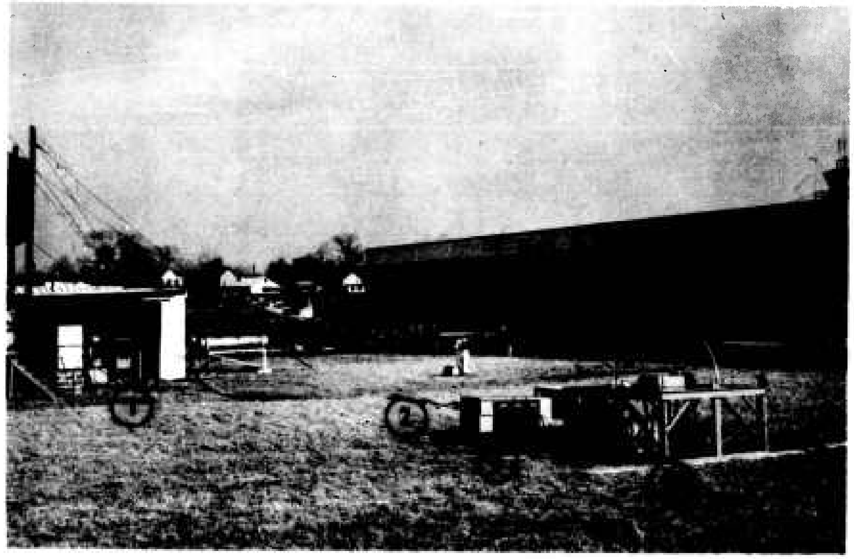


Figure 6 Test Site

1. Recording Instrumentation
2. Instrumentation Cable
3. Load Banks
4. Test Stand

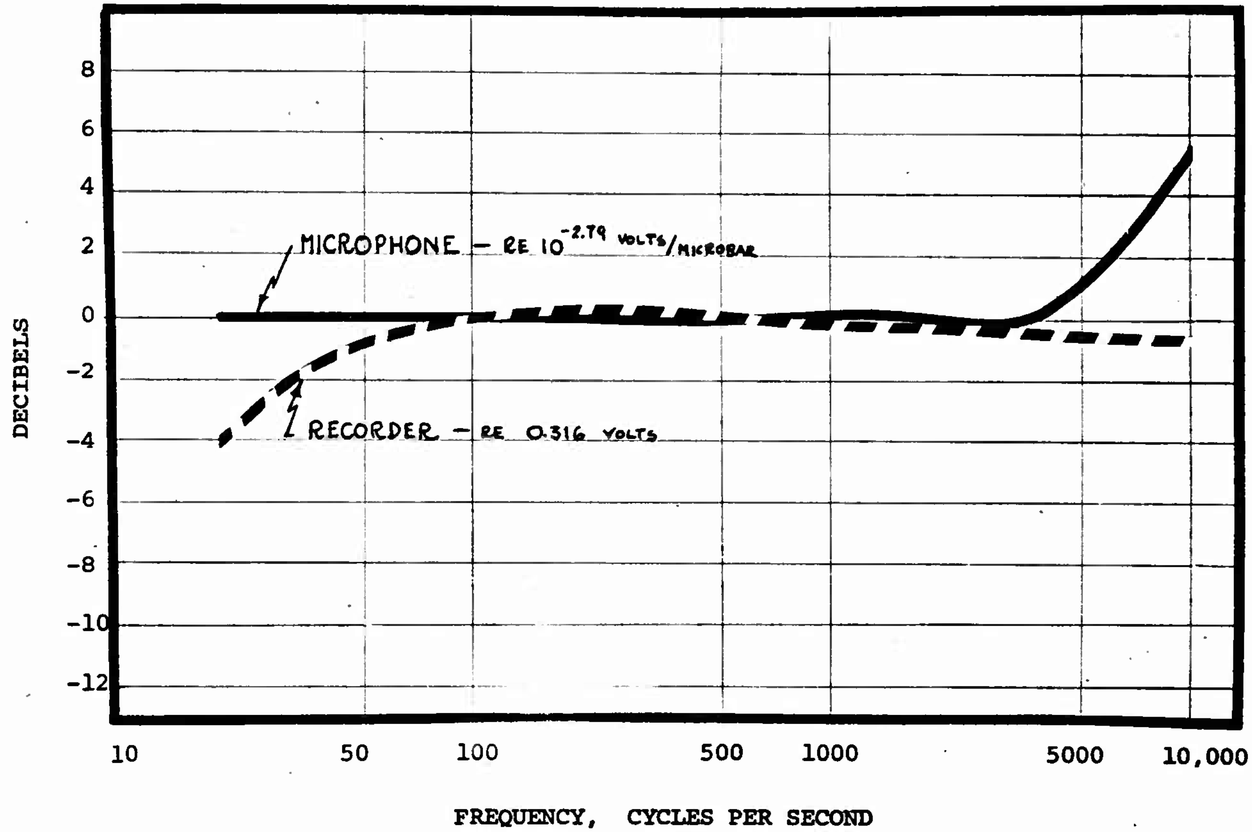


Figure 7. Frequency Response of Air-Borne Noise System

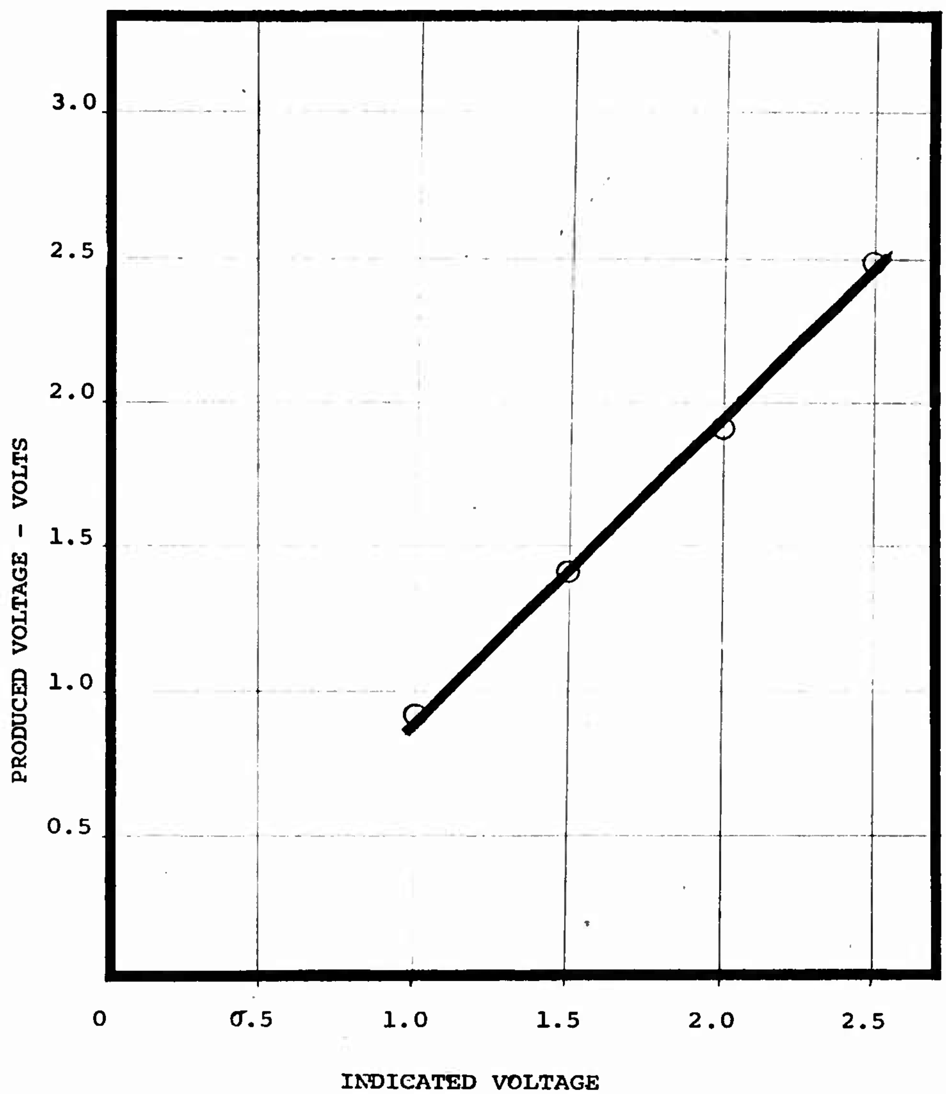


Figure 8. Voltmeter Instrument Error

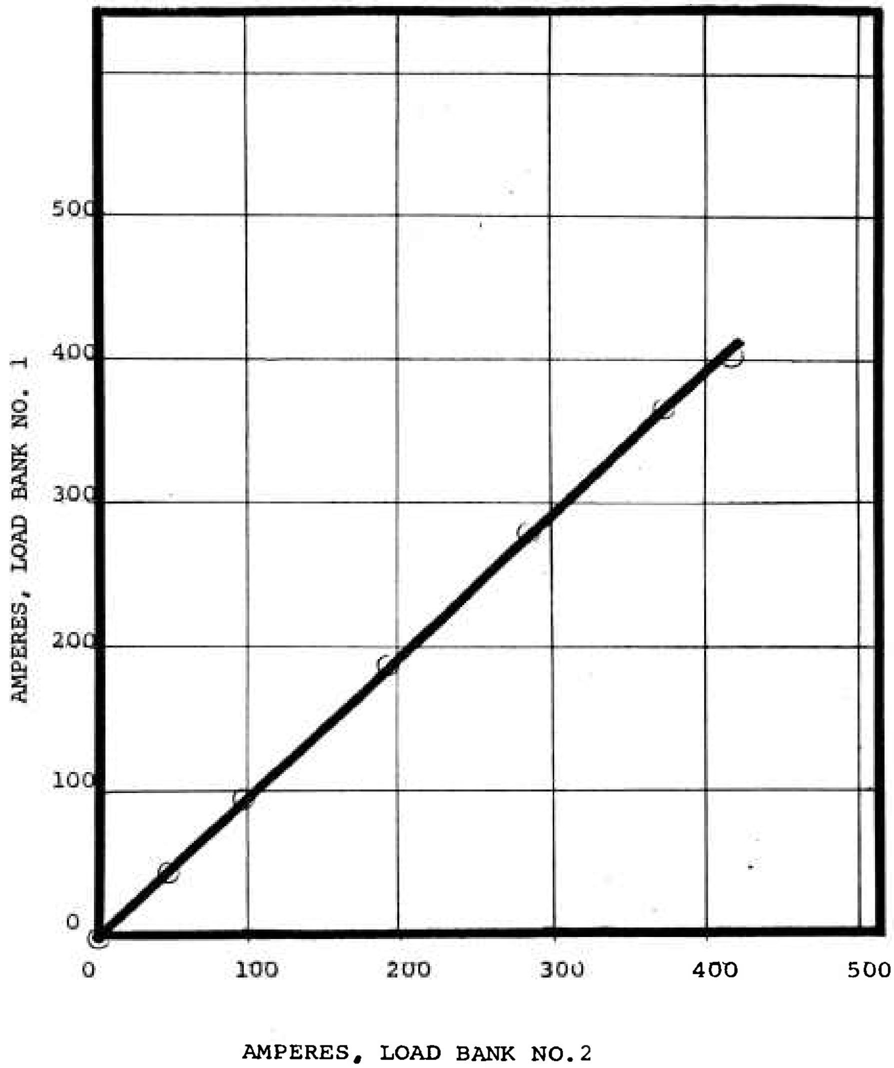


Figure 9. Ammeter Instrument Error

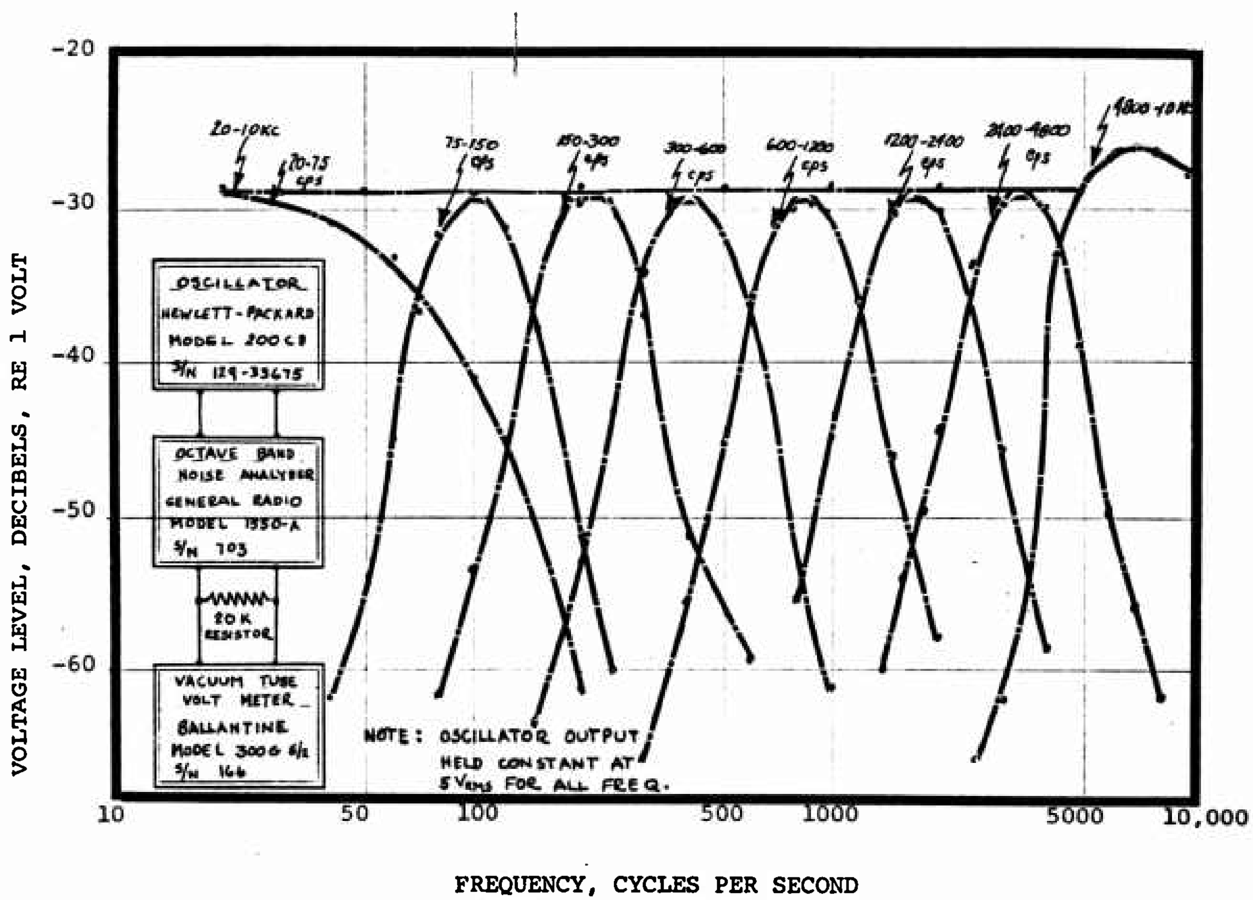


Figure 10. Frequency Response of Octave Band Analyzer

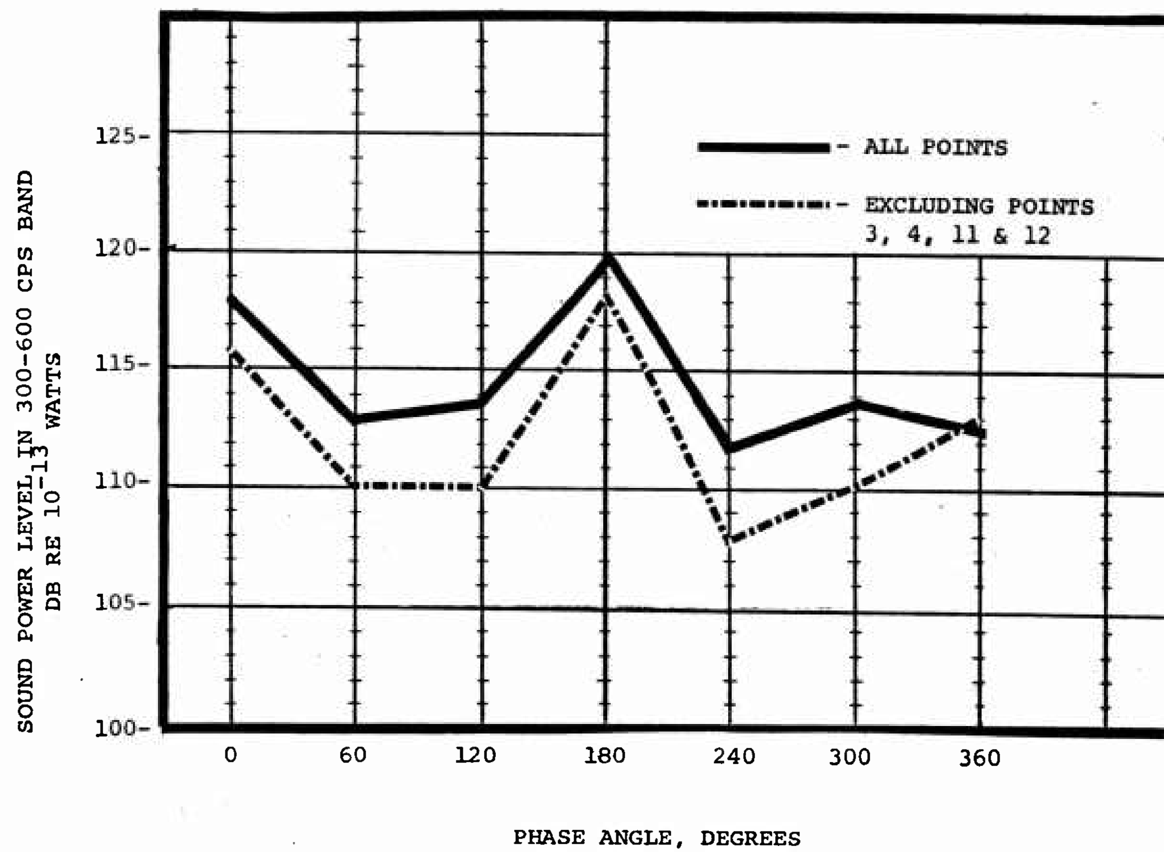


Figure 11. Sound Power Level as Affected by Phasing Between Two Identical Gear Sets

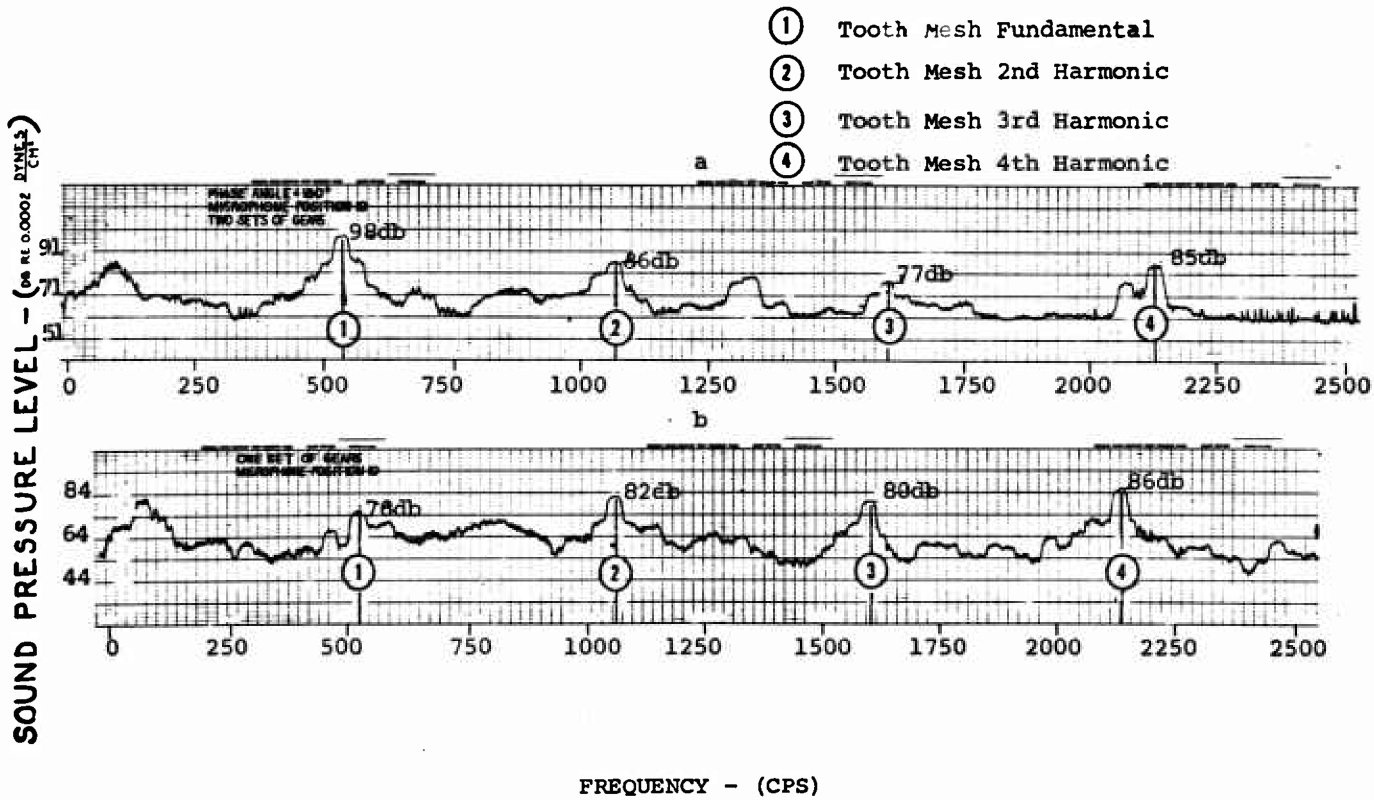


Figure 12. Gear Noise Spectra

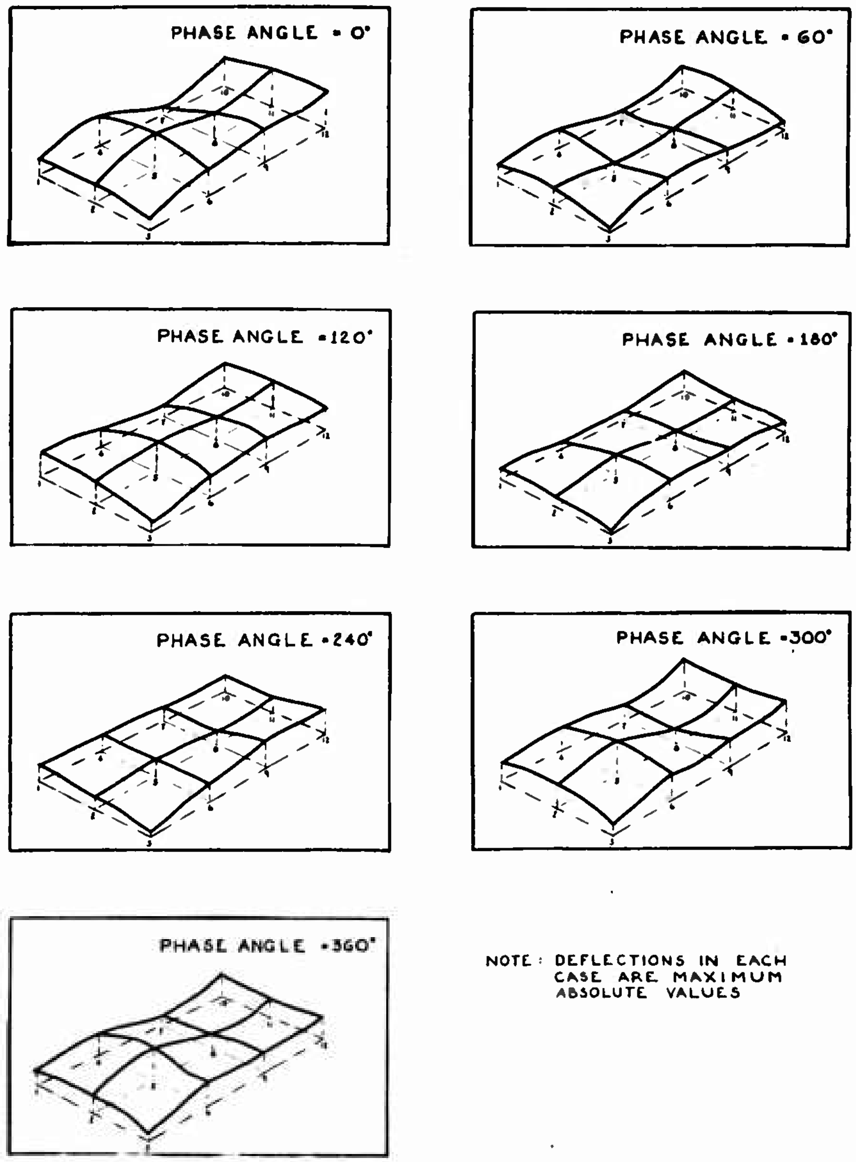


Figure 13. Deflection Pattern of Gear Case Cover

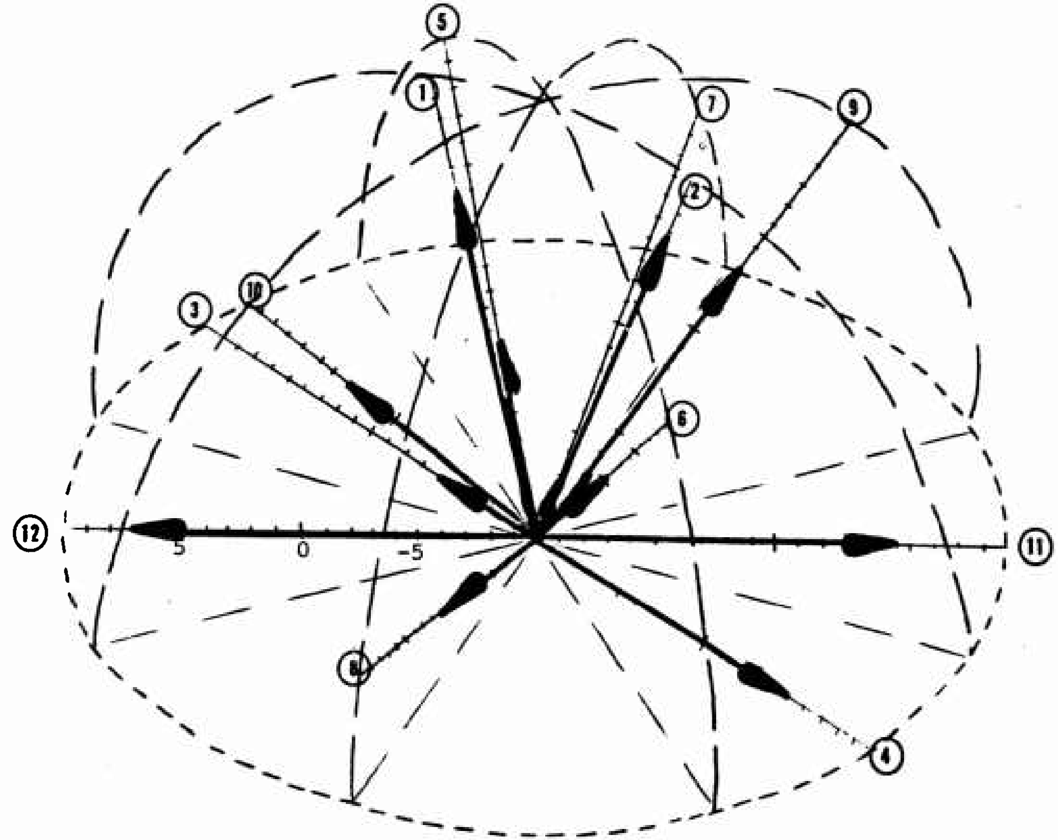


Figure 14. Directivity Indexes at Phase Angle 0°

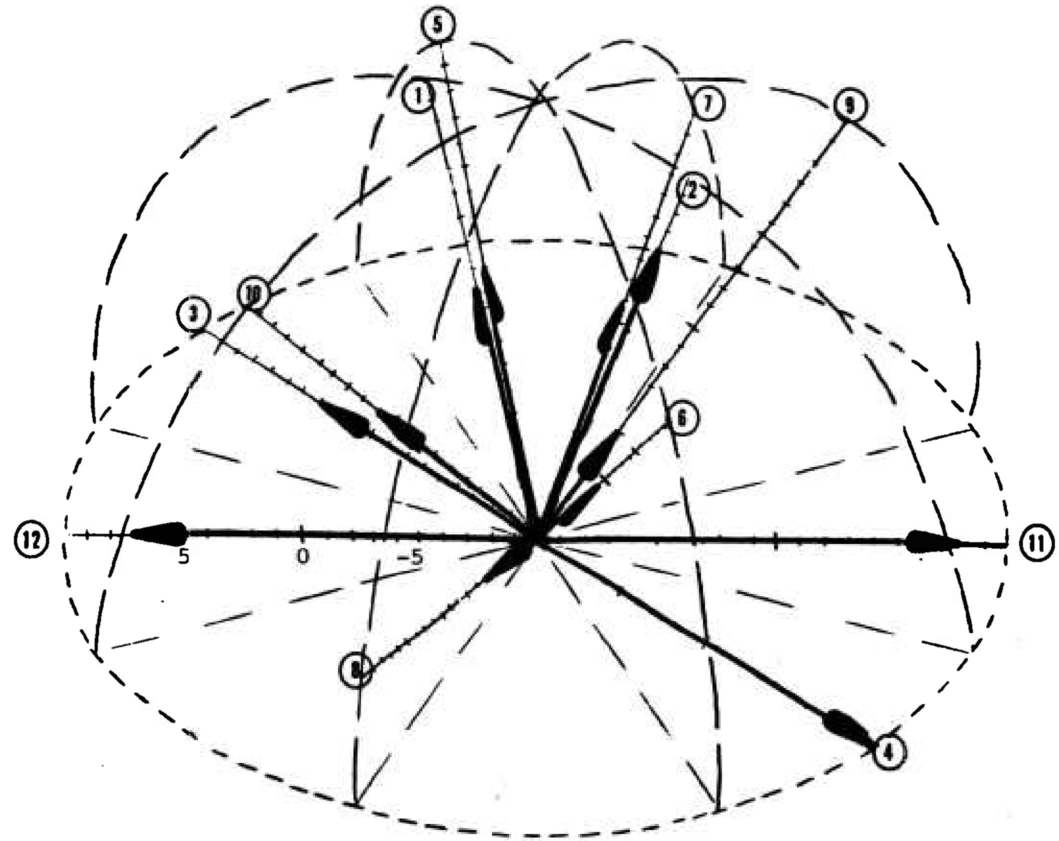


Figure 15. Directivity Indexes at Phase Angle 60°

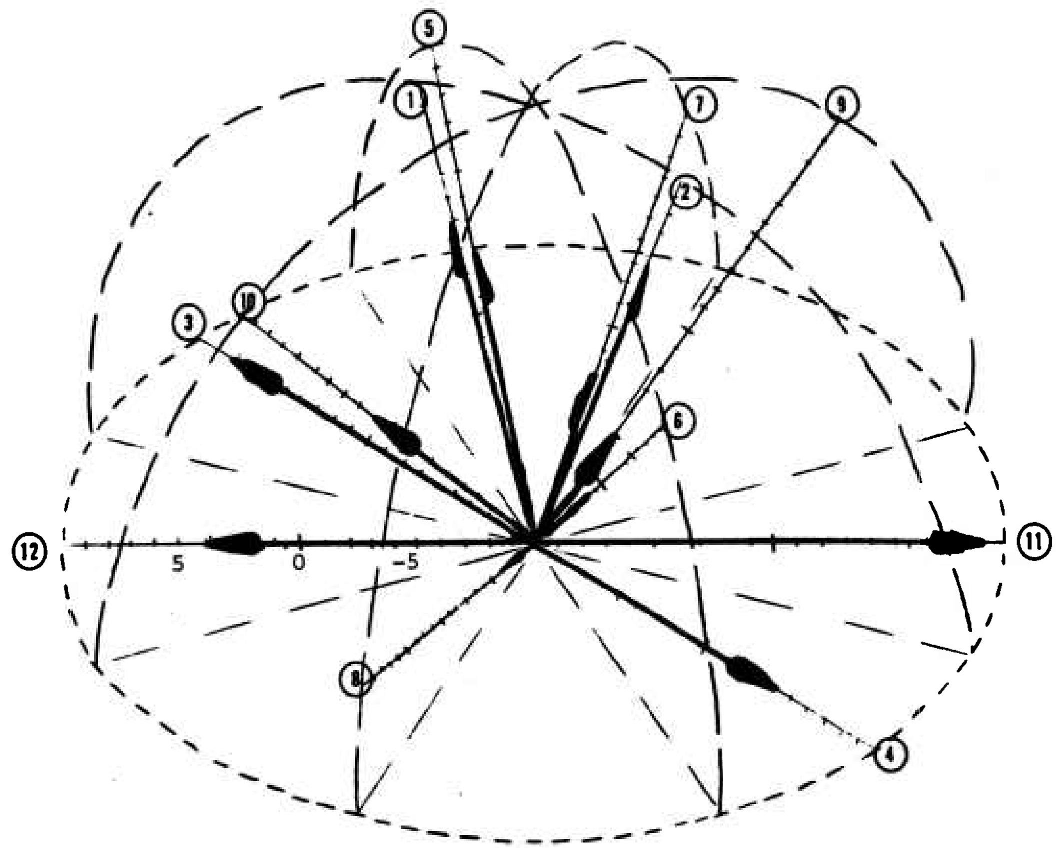


Figure 16. Directivity Indexes at Phase Angle 120°

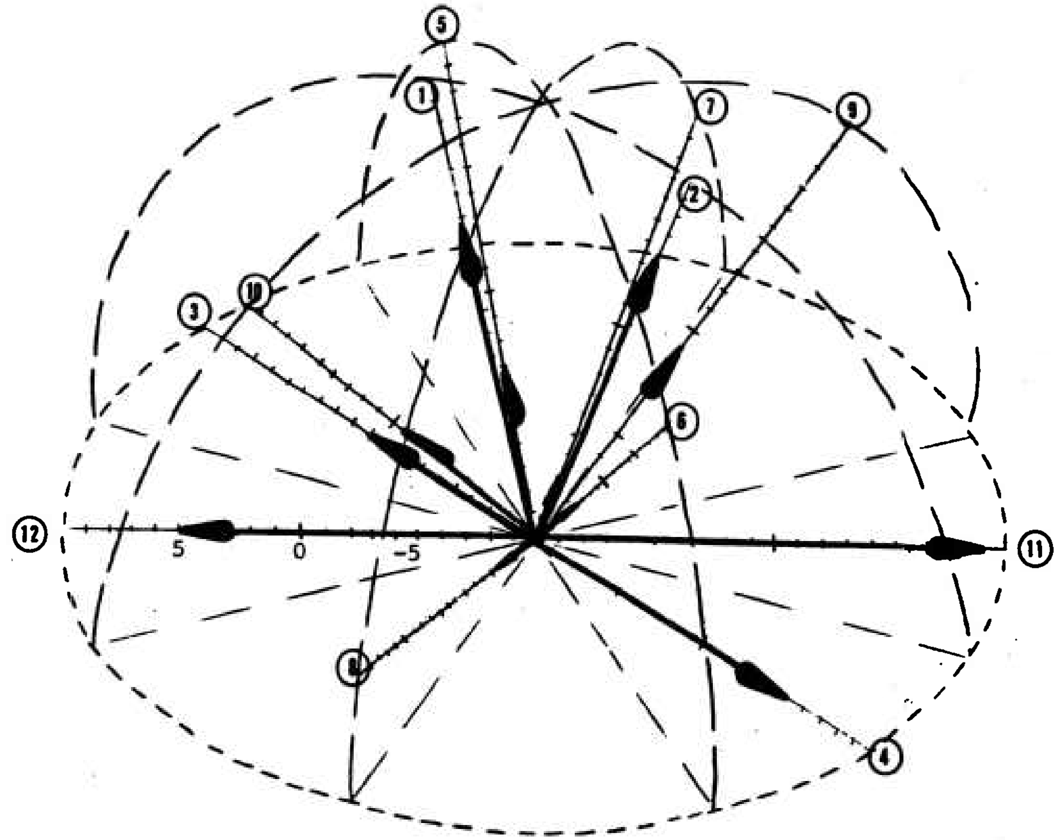


Figure 17. Directivity Indexes at Phase Angle 180°

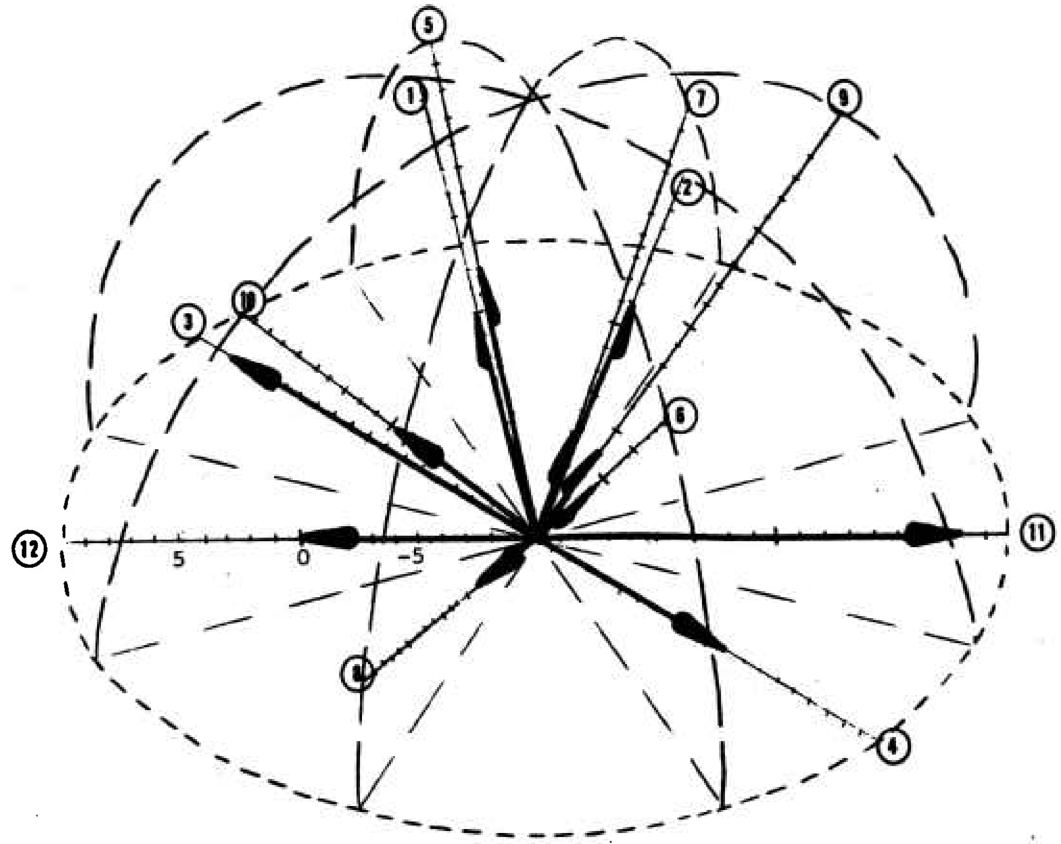


Figure 18. Directivity Indexes at Phase Angle 240°

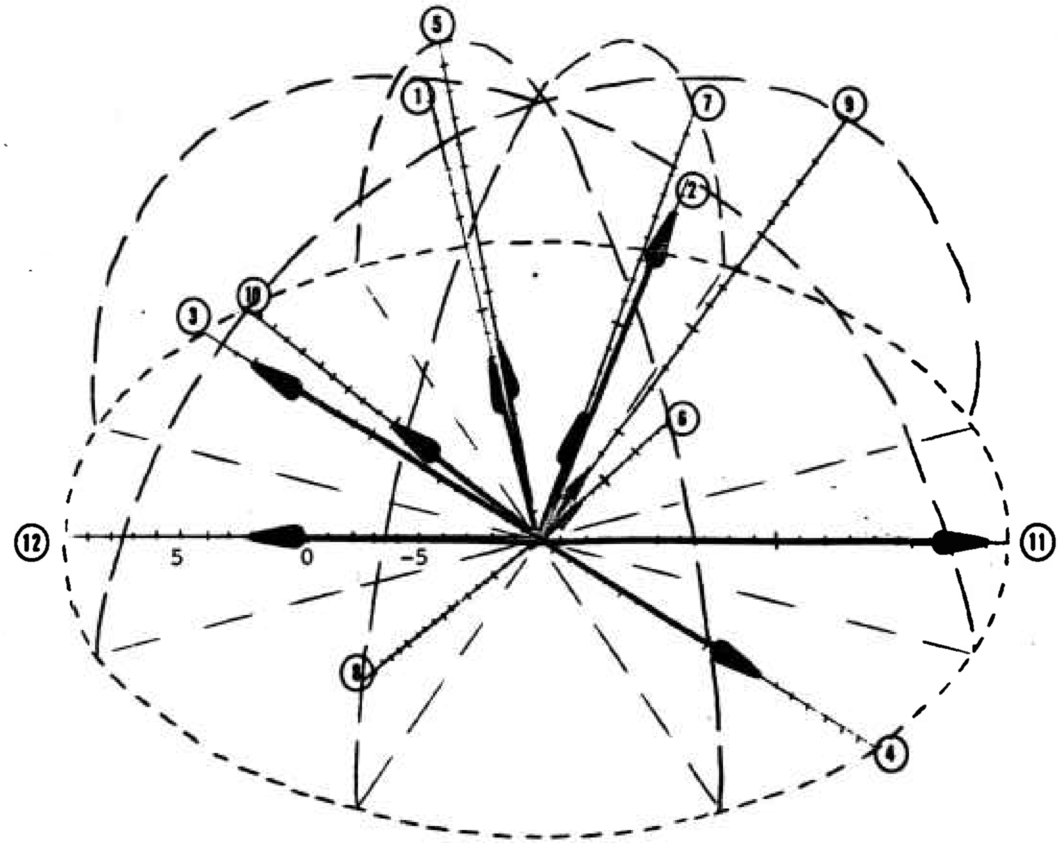


Figure 19. Directivity Indexes at Phase Angle 300°

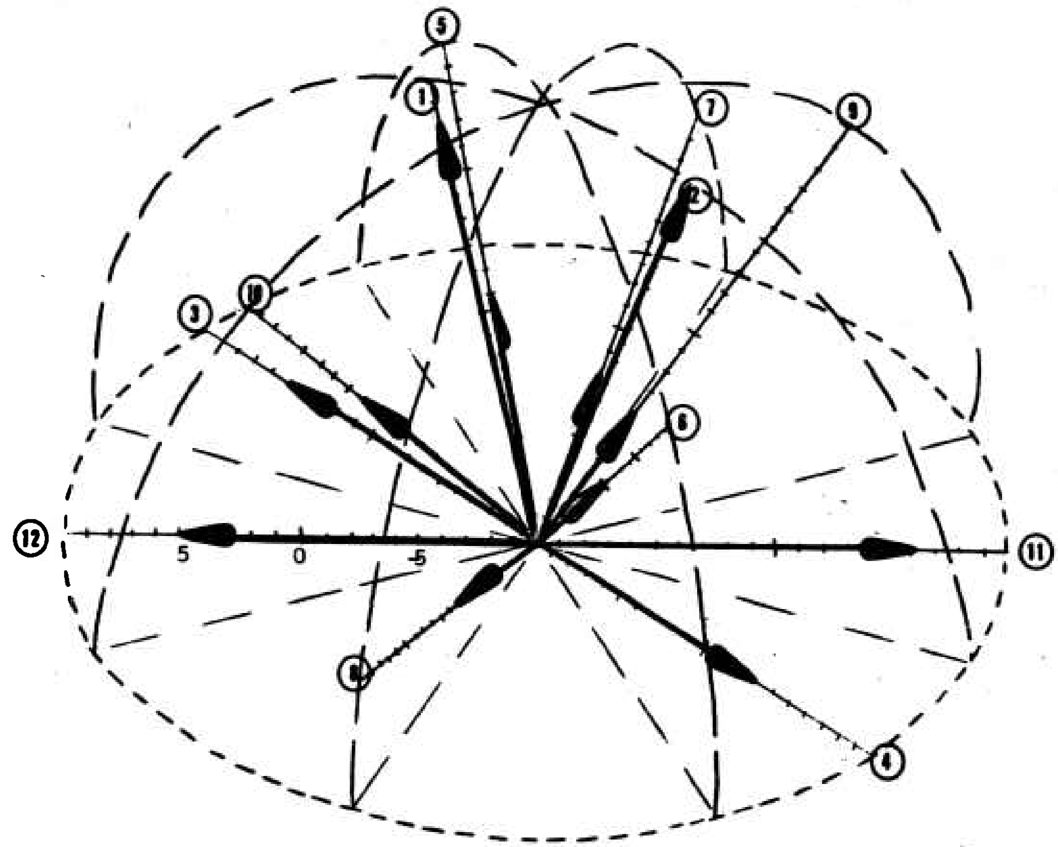


Figure 20. Directivity Indexes at Phase Angle 360°

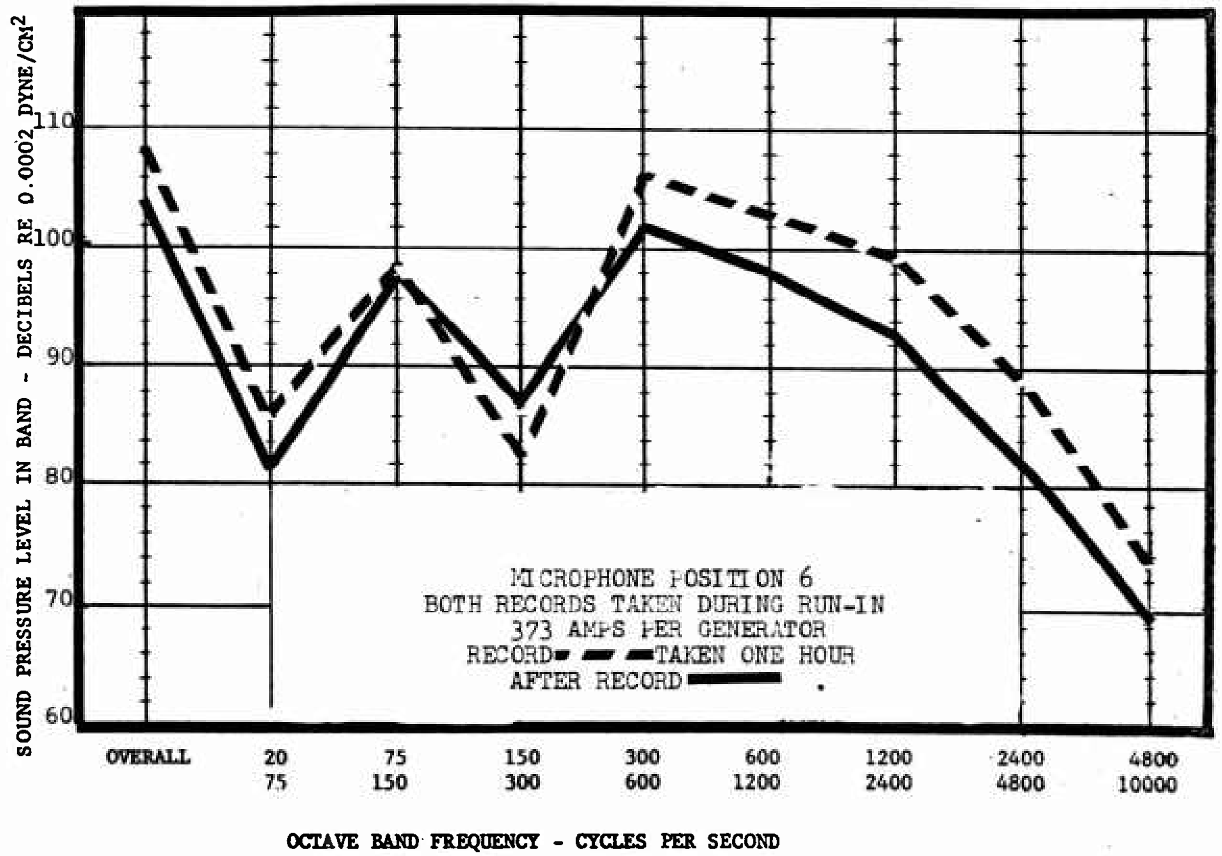
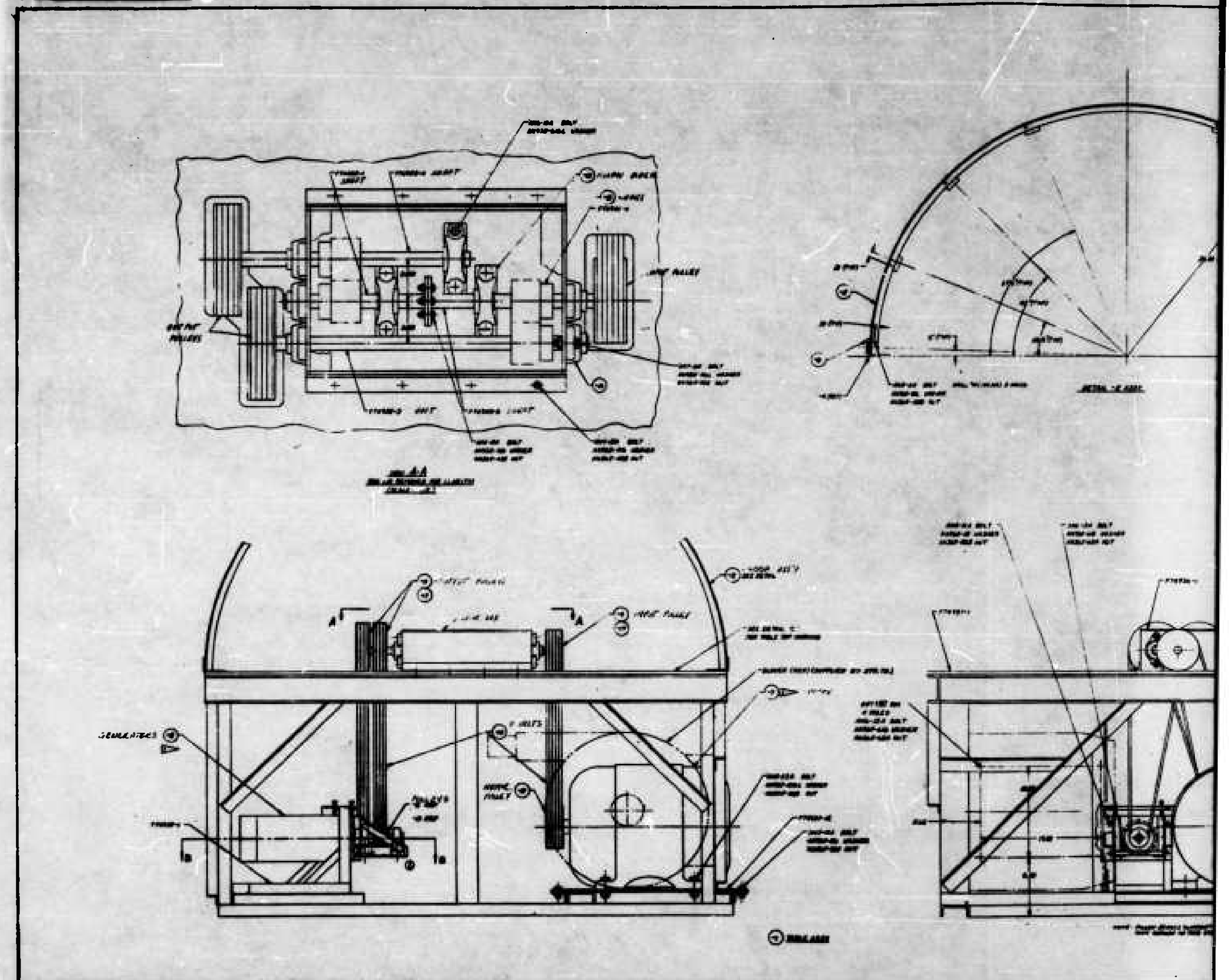


Figure 21. Acoustical Detection of Gear Wear

1



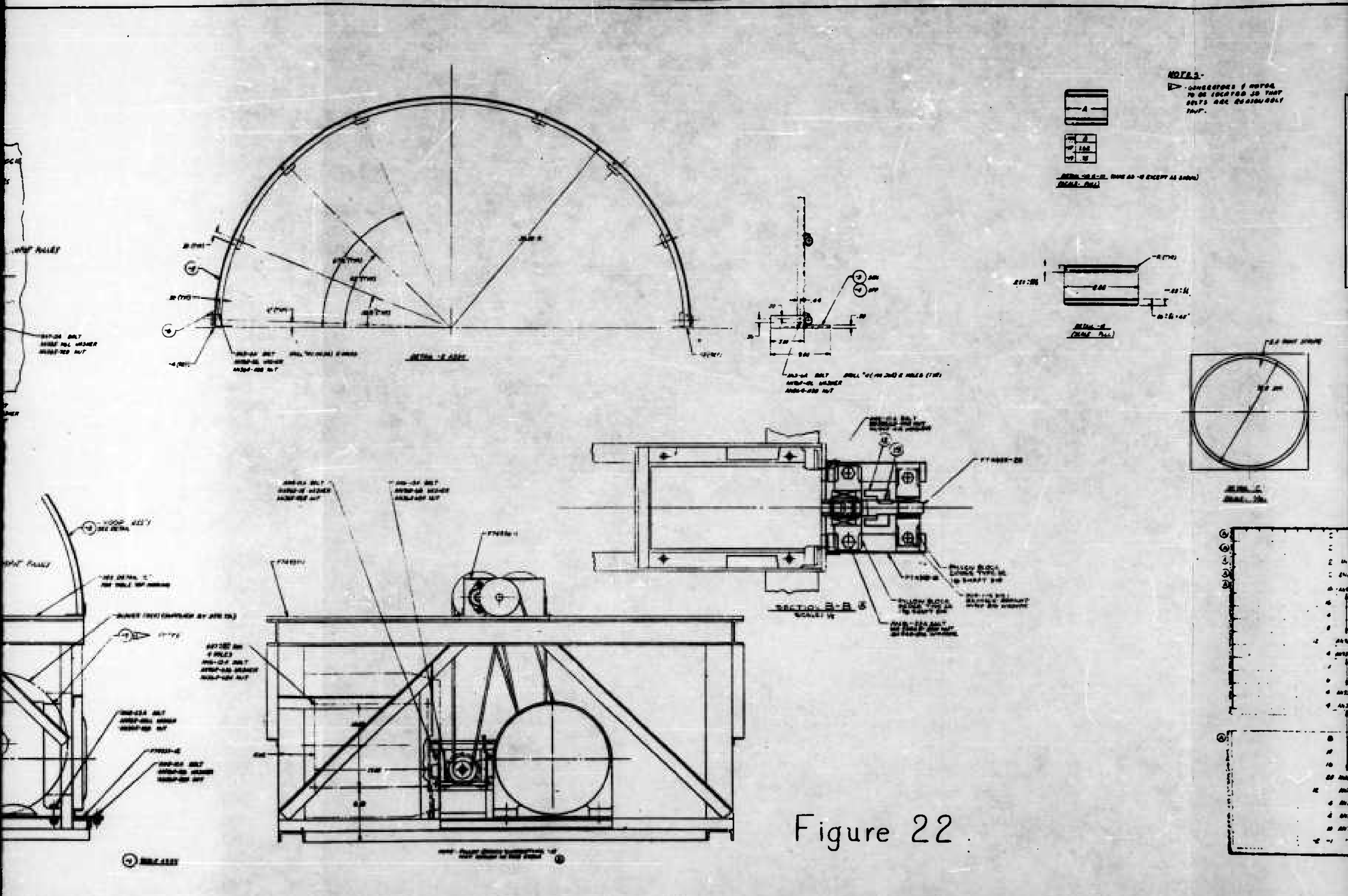


Figure 22

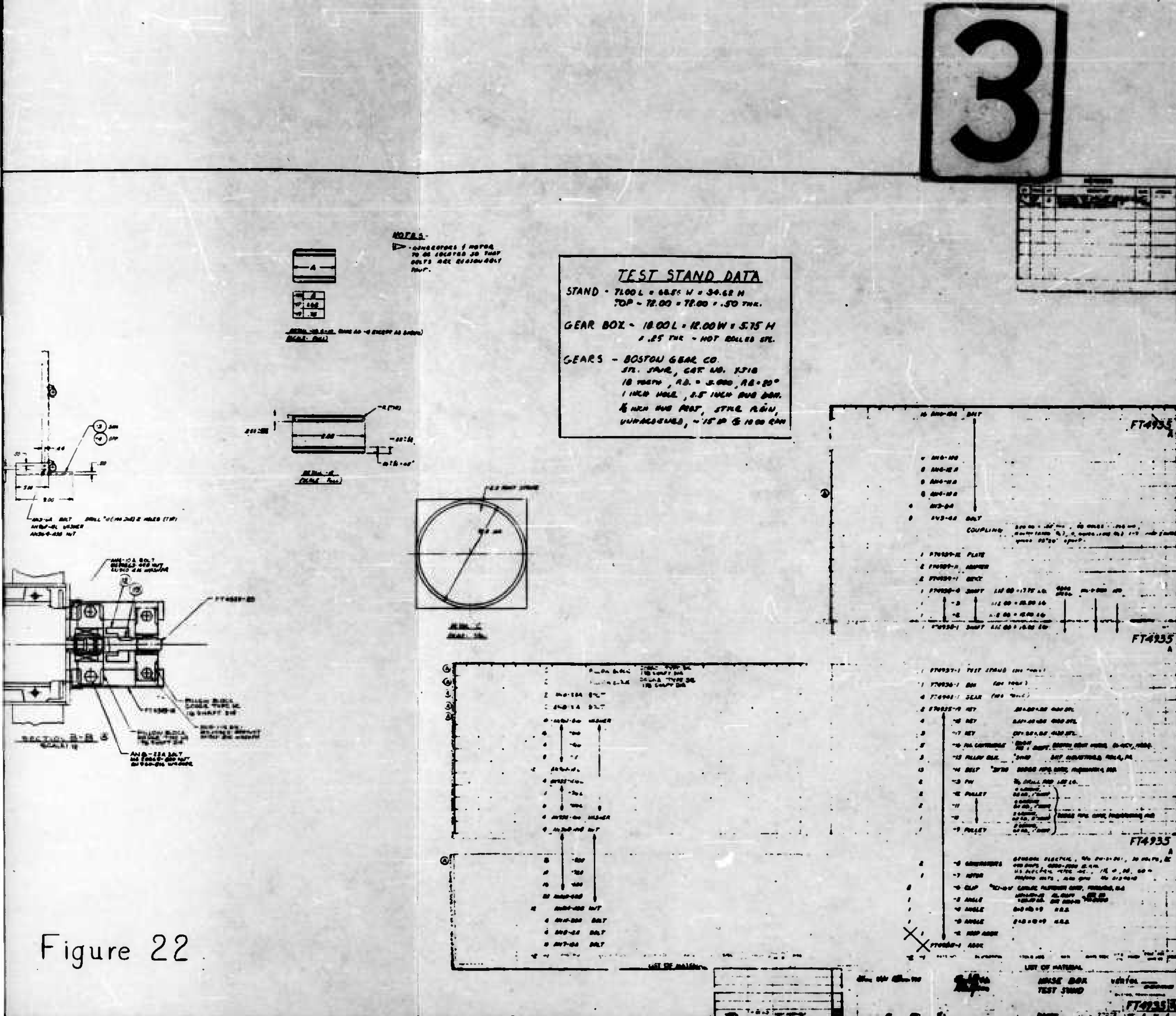


Figure 22

4565-62

APPENDIX IV

DATA

AIR-BORNE NOISE TEST DATA

PHA ANG	MIC POS	SPL 300-600 CPS BAND	DI	REC NO.	LOAD VOLT	ONE AMP	LOAD VOLT	TWO AMP	GEAR RPM
0°	1	102	5	84	26.5	212	26.5	212	1750
"	2	103	6	83	"	"	"	"	"
"	3	96	-4	90	"	"	"	"	"
"	4	105	5	89	"	"	"	"	"
"	5	95	-2	80	"	"	"	"	"
"	6	98	1	76	"	"	"	"	"
"	7	90	-7	86	"	"	"	"	"
"	8	98	1	85	"	"	"	"	"
"	9	100	3	82	"	"	"	"	"
"	10	100	3	81	"	"	"	"	"
"	11	105	5	88	"	"	"	"	"
"	12	107	7	87	26.5	212	26.5	212	1750
60°	1	94	1	379	"	218	26.9	218	1760
"	2	99	6	380	"	"	"	"	"
"	3	99	3	381	"	"	"	"	"
"	4	105	10	382	"	"	"	"	"
"	5	93	1	385	26.7	210	26.7	210	1760
"	6	92	-1	386	"	"	"	"	"
"	7	93	1	387	26.8	"	26.9	"	"
"	8	89	-4	388	"	"	"	"	"
"	9	88	-5	389	"	"	"	"	"
"	10	94	1	390	27.0	"	"	"	"
"	11	104	8	383	26.5	218	26.9	218	"
"	12	103	7	384	"	"	"	"	"
120°	1	97	4	363	26.2	215	26.5	215	1740
"	2	98	5	364	"	"	"	"	"
"	3	104	8	365	"	"	"	"	"
"	4	100	4	367	"	"	"	"	"
"	5	95	2	369	26.5	212	26.5	212	1750
"	6	91	-2	370	"	"	"	"	"
"	7	91	-2	371	"	"	"	"	"
"	8	87	-6	372	26.8	"	26.8	210	1760
"	9	94	-5	374	"	"	"	"	"
"	10	88	1	373	"	"	"	"	"
"	11	105	9	368	26.2	215	26.5	215	1740
120°	12	100	4	366	26.2	215	26.5	215	1740

AIR-BORNE NOISE TEST DATA

PHA ANG	MIC POS	SPL 300-600 CPS BAND	DI	REC NO.	LOAD ONE VOLT	LOAD ONE AMP	LOAD TWO VOLT	LOAD TWO AMP	GEAR RPM
180°	1	103	4	180	26.6	217	27.0	220	1740
"	2	105	6	181	"	"	"	"	"
"	3	106	0	185	"	"	"	"	"
"	4	108	5	182	"	"	"	"	""
"	5	103	-3	186	26.4	210	26.7	215	1735
"	6	103	-3	187	"	"	"	"	"
"	7	92	-7	191	26.6	212	27.0	212	1735
"	8	95	-5	190	26.6	213	26.8	213	1735
"	9	98	-1	188	"	"	"	"	"
"	10	99	-1	189	"	"	"	"	"
"	11	110	9	183	"	217	27.0	220	1740
"	12	107	5	184	"	"	"	"	"
240°	1	92	0	289	27.0	210	26.9	210	1760
"	2	95	3	291	"	"	"	"	"
"	3	103	8	292	"	"	"	"	"
"	4	96	1	293	"	"	"	"	"
"	5	93	1	285	26.7	210	26.7	210	1795
"	6	92	-1	286	"	"	"	"	"
"	7	87	-5	283	26.6	215	26.6	210	1795
"	8	90	-3	282	26.4	218	26.6	218	1755
"	9	86	-6	288	27.0	210	26.9	210	1755
"	10	92	0	287	"	"	"	"	"
"	11	103	8	294	27.0	210	27.0	210	1760
"	12	95	0	290	"	"	26.9	210	1760
300°	1	91	-2	268	26.2	218	26.6	218	1760
"	2	102	8	270	"	"	"	"	"
"	3	103	7	272	"	"	"	"	"
"	4	99	3	271	"	"	"	"	"
"	5	91	-2	277	27.0	210	26.9	210	"
"	6	90	-3	276	"	"	"	"	"
"	7	89	-4	279	"	"	27.0	"	"
"	8	84	-9	278	27.0	210	26.9	210	"
"	9	86	-7	275	26.6	210	26.6	210	"
"	10	94	0	274	"	"	"	"	"
"	11	105	9	273	"	"	"	"	"
300°	12	98	2	269	26.2	218	26.6	218	1760

AIR-BORNE NOISE TEST DATA

PHA ANG	MIC POS	SPL 300-600 CPS BAND	DI	REC NO.	LOAD VOLT	ONE AMP	LOAD VOLT	TWO AMP	GEAR RPM
360°	1	100	8	347	26.5	218	26.6	218	1750
"	2	102	10	348	"	"	"	"	"
"	3	100	5	349	"	"	"	"	"
"	4	98	3	352	"	"	"	"	"
"	5	92	0	353	26.5	212	26.5	212	"
"	6	93	-1	354	"	"	"	"	"
"	7	90	-2	356	"	"	"	"	"
"	8	91	-1	355	"	"	"	"	"
"	9	88	4	357	26.7	210	26.7	210	1760
"	10	94	2	358	"	"	"	"	"
"	11	104	6	351	26.5	218	26.6	218	1750
360°	12	100	5	350	26.5	218	26.6	218	1750

STRUCTURE-BORNE NOISE TEST DATA

PHA ANG	ACC POS	VOLT 300-600 CPS BAND	DISP 300-600 CPS BAND	REC NO.	LOAD VOLT	ONE AMP	LOAD VOLT	TWO AMP	GEAR RPM
0°	1	.31	5.15	93	26.7	220	26.8	220	1760
"	2	.35	5.67	94	26.8	218	"	218	"
"	3	.18	3.09	95	"	"	27.0	"	1750
"	4	.52	8.76	96	"	"	26.8	"	"
"	5	.70	11.60	97	"	"	"	"	"
"	6	.46	7.75	98	"	"	"	"	1760
"	7	.15	2.58	99	"	"	26.9	"	"
"	8	.39	6.45	100	27.0	220	26.8	220	1750
"	9	.56	9.04	101	"	"	26.9	"	"
"	10	.56	9.04	102	"	219	26.8	"	"
"	11	.70	11.60	103	26.8	"	"	219	1770
0°	12	.66	10.30	104	26.7	"	"	"	1760
60°	1	.22	3.87	112	26.4	217	26.7	217	1740
"	2	.31	5.15	114	26.7	220	26.9	220	"
"	3	.09	0.13	116	"	"	26.8	"	"
"	4	.34	5.61	118	27.0	"	27.0	"	"
"	5	.16	2.84	124	26.4	218	26.7	218	1730
"	6	.32	5.32	126	26.8	220	27.0	220	1710
"	7	.12	2.06	143	27.0	"	27.1	"	1740
"	8	.21	3.62	141	"	"	27.0	"	1750
"	9	.25	4.39	133	26.5	217	26.8	217	1760
"	10	.40	7.21	139	27.0	220	27.0	220	1745
"	11	.39	6.45	135	"	"	27.2	"	1750
"	12	.14	2.32	137	26.8	"	27.0	"	"
120°	1	.39	6.70	163	"	210	26.8	210	1745
"	2	.41	6.07	164	"	"	"	"	"
"	3	.16	2.84	165	"	"	"	"	"
"	4	.34	5.67	166	"	"	27.0	"	1750
"	5	.48	8.25	167	"	"	"	"	"
"	6	.35	5.94	168	"	"	"	"	"
"	7	.22	3.87	169	"	"	"	"	"
"	8	.41	6.95	170	"	"	"	"	"
"	9	.45	7.75	171	"	"	"	"	"
"	10	.47	8.00	172	"	"	"	"	"
"	11	.43	7.22	173	"	"	"	"	"
120°	12	.37	6.20	174	26.9	210	27.0	210	1745

STRUCTURE-BORNE NOISE TEST DATA

PHA ANG	ACC POS	VOLT 300-600 CPS BAND	DISP 300-600 CPS BAND	REC NO.	LOAD VOLT.	ONE AMP	LOAD VOLT	TWO AMP	GEAR RPM
180°	1	.21	3.61	192	26.5	220	26.6	220	1740
"	2	.20	3.61	193	"	"	"	"	"
"	3	.08	0.13	194	"	"	26.5	"	"
"	4	.16	2.84	195	"	"	"	"	"
"	5	.35	5.93	196	"	"	"	"	"
"	6	.32	5.67	197	"	"	"	212	1745
"	7	.17	3.10	198	"	"	"	"	"
"	8	.20	3.61	199	"	"	"	"	"
"	9	.30	5.16	200	"	"	26.6	210	1740
"	10	.38	6.45	201	"	"	"	"	
"	11	.23	4.13	202	"	"	"	"	"
"	12	.18	3.10	203	26.6	"	"	"	"
240°	1	.29	5.15	206	26.3	220	26.6	220	1750
"	2	.21	3.61	207	"	"	"	"	"
"	3	.10	1.81	208	26.7	220	26.9	220	1750
"	4	.32	5.32	209	"	"	"	"	"
"	5	.30	5.15	210	"	"	"	"	"
"	6	.31	5.15	211	"	"	"	"	"
"	7	.25	4.39	212	26.6	215	26.6	215	1750
"	8	.22	3.87	213	"	"	"	"	"
"	9	.46	7.75	214	"	"	"	"	"
"	10	.32	5.32	215	"	"	"	"	"
"	11	.25	4.39	216	"	"	"	"	"
"	12	.41	6.95	211	"	"	"	"	"
300°	1	.32	5.32	220	26.7	218	26.6	215	1740
"	2	.40	6.70	221	"	"	"	"	"
"	3	.19	3,35	222	"	"	"	"	"
"	4	.45	7.75	223	"	"	"	"	"
"	5	.62	10.30	224	26.7	218	26.7	212	1750
"	6	.44	7.50	225	"	"	"	"	"
"	7	.28	4.90	226	"	"	"	"	"
"	8	.24	4.13	227	"	"	"	"	"
"	9	.45	7.75	228	"	"	"	210	"
"	10	.56	9.30	229	"	"	"	"	"
"	11	.50	8.53	230	"	"	"	"	"
300°	12	.54	9.30	231	26.7	218	26.7	210	1750

STRUCTURE-BORNE NOISE TEST DATA

PHA ANG	ACC POS	VOLT 300-600 CPS BAND	DISP 300-600 CPS BAND	REC NO.	LOAD VOLT	ONE AMP	LOAD VOLT	TWO AMP	GEAR RPM
360°	1	.28	4.90	234	26.4	220	28.6	220	1750
"	2	.30	5.16	235	"	"	"	"	"
"	3	.14	2.58	236	"	"	"	"	"
"	4	.40	6.70	237	26.5	218	28.6	213	1750
"	5	.60	10.30	238	"	"	"	"	"
"	6	.40	6.70	239	"	"	"	"	"
"	7	.18	3.10	240	"	"	"	"	"
"	8	.24	4.13	241	26.6	"	"	210	"
"	9	.35	5.94	242	"	"	"	"	"
"	10	.44	7.50	243	"	"	"	"	"
"	11	.35	5.94	244	"	"	"	"	"
360°	12	.39	6.45	245	26.7	220	26.7	210	1750

DISTRIBUTION

USCONARC	2
Surg Gen, DA	1
USAIC	1
USA AVNS, CDO	2
USARM BD	1
USA AVN BD	2
USATMC (FTZAT), ATO	1
DCSLOG	2
DCSOPS	1
ARO, OCRD	1
OCRD, DA	1
USATAFO, BUWEPS, DN	1
NATC	2
USAOMC	1
Ord Bd	1
QMRECOMD	1
Sig Bd	1
CofT	6
USATCDG	1
USATMC	2
USATSCH	3
USATRECOM	35
USATRECOM LO, Wright-Patterson AFB	1
AR & D, Andrews AFB	1
WADD, Wright-Patterson AFB	2
USAF (AFDFD)	1
CNR	1
BUWEPS, DN	1
MCLO, USATSCH	1
USCG	1
NAFEC	1
NASA, Washington, D.C.,	2
BRAS, DAQMG (Mov & Tn)	3
ASTIA	10
Langley Rsch Cen, NASA	4
Ames Rsch Cen, NASA	1
Lewis Rsch Cen, NASA	1
USA Hosp, Ft. Rucker	1
USAMR DC	1

QMRECOMD	1
CRD, CoS, ASP	1
USATRECOM LO, USARDG (9851DU)	1
USATRECOM LO, USAABELCT BD	1
USATB	1

Vertol Division, The Boeing Company, Morton, Pennsylvania INVESTIGATION TO DETERMINE THE EFFECT OF PHASING ON THE NOISE GENERATED BY SPUR GEARS - TCREC Technical Rept 62-49, April 1962, 57 pp. 21 illus. 6 tables, (Contract DA 44-177-TC-777) USATRECOM Task 9R38-01-017-54

Unclassified Report

A test program was performed to evaluate the effect of relative gear tooth contact phasing on the acoustical characteristics of a model

1. Gear Noise
2. Gear Noise Reduction by Phasing

I Muehl, C. L.
II Sternfeld, H.Jr.
III Contract DA 44-177-TC-777

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